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# Condition assessment of cycle path texture and evenness using a bicycle measurement trailer

Martin Larsson <sup>a,b</sup>, Anna Niska <sup>a</sup>, Sigurdur Erlingsson <sup>a,b,c</sup>, Mattias Tunholm <sup>a</sup> and Peter Andrén <sup>a</sup>

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## ABSTRACT

Cyclists' riding comfort, related to pavement texture and unevenness, has not been thoroughly investigated, partly due to the lack of condition assessment methods specifically adapted to the speed and space limits on cycle paths. Metrics that better describe the perceived comfort of cyclists, rather than that of car users, are needed. In this paper a novel method, the Bicycle Measurement Trailer (BMT), is proposed to bridge this gap. Eight different cycle path surface types have been assessed with regards to pavement texture and for four of these surfaces the longitudinal evenness was assessed. The accuracy and repeatability of the BMT were evaluated. Finally, five different metrics (Dynamic Comfort Index, Evenness Coefficient, 0.5 m Straight Edge, International Roughness Index and Root Mean Square), were calculated from the collected data and assessed. The main findings suggest that the BMT has a high accuracy at normal and high cycling speeds and a high level of repeatability at normal cycling speed. The surfaces could be ranked according to texture, and the evenness was successfully analysed. In conclusion, the BMT could be a valuable tool to assess the cycle path surface condition in relation to bicycle riding comfort.

Abbreviations: AC: Asphalt Concrete; BCBP\*: Big Concrete Block Pavement; BMT\*: Bicycle Measurement Trailer; DCI: Dynamic Comfort Index; EC: Evenness Coefficient; FFT: Fast Fourier Transformation; G\*: Gravel; IRI: International Roughness Index; MPD: Mean Profile Depth; NAC\*: New Asphalt Concrete; OCAC\*: Old Cracked Asphalt Concrete; OUAC\*: Old Uncracked Asphalt Concrete; PSD: Power Spectral Density; RLAC\*: Recently Laid Asphalt Concrete; RMS: Root Mean Square; RST: Road Surface Tester; SCBP\*: Small Concrete Block Pavement; SE: Straight Edge; VTI: Swedish National Road and Transport Research Institute; WF\*: Workshop Floor; \*Abbreviations that has been used for this paper specifically

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Cycling comfort; cycle paths; road surface measurements; surface evenness; surface texture

## 1. Introduction

In recent years there has been an increase in the focus on cycling (Joo *et al.* 2015), and several countries have national policies to increase the modal share of cycling (Linden and Bohrmann 2012, Swedish government 2017). Some factors are known to affect this modal choice, such as the local weather condition, i.e. precipitation (Nankervis 1999, Bergström and Magnusson 2003), wind and temperature (Bergström and Magnusson 2003), along with traffic safety issues and the extent and condition of the cycle infrastructure (Hull and O'Holleran 2014). A continuous cycle path network affects the willingness to cycle (Alm and Koglin 2020) but the road surface condition of the cycle paths is also important (Landis *et al.* 1997, Lee and Moudon 2008), not least for traffic safety reasons, especially in relation to single bicycle crashes (Scheppers and Klein Wolt 2012). Moreover, it has been suggested that narrow cycle paths are a problem for the cyclists (Cairney and King 2003), and road surface deficiencies provide even less space as the cyclists will try to avoid these deficiencies.

The cyclists' comfort related to the texture (i.e. deviation of a pavement surface from a true planar surface, with a texture wavelength less than 0.5 m) and unevenness (i.e. deviation of a pavement surface from a true planar surface with the characteristic dimensions of the surface between 0.5 and 50 m, corresponding to wavelengths with one-third-octave bands including the range 0.63 m to 50 m of centre wavelengths) (ISO 2002) of the surface is another important aspect. However, this is often not included in the indices used to predict cyclists' perceptions of roadway environments (Harkey *et al.* 1998) or in the bicycle infrastructure design manuals (Barrero and Rodriguez-Valencia 2021). The vibrations to which the cyclists are subjected, which are caused by acceleration from riding over a rough surface, are an important factor and constitute an approach that has been used in several studies to measure these accelerations while riding on surfaces with different roughness (Giubilato and Petrone 2012, Hölzel *et al.* 2012, Olieman *et al.* 2012, Joo and Oh 2013, Yamanaka *et al.* 2013, Niska and Sjögren 2014, Bíl *et al.* 2015, Gao *et al.* 2018, Litzemberger

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*et al.* 2018, Zang *et al.* 2018). Some of these studies have simultaneously investigated the perceived comfort by test cyclists and found correlations between acceleration and perceived comfort. For example, from Niska and Sjögren (2014) and Bíl *et al.* (2015) it is clear that the test cyclists rate concrete block pavement as less comfortable than old asphalt, which in turn is less comfortable than new asphalt. Furthermore, Hölzel *et al.* (2012) also found similar results, with concrete slabs being less comfortable than asphalt surfaces when comparing acceleration measurements with level of perceptibility to vibrations according to German standards.

However, there are some limitations to such approaches. Various co-existing factors affect the acceleration, such as tyre pressure and the cycling speed (Olieman *et al.* 2012), type of bicycle (Gao *et al.* 2018), bicycle suspension (Chou *et al.* 2015), the weight of the rider (Chou *et al.* 2015) and possibly wheel types (Giubilato and Petrone 2012). Moreover, the type of accelerometer is important (Niska and Sjögren 2014), as well as where it is mounted on the bicycle, as the vibrations affect the rider differently with respect to which body part is subjected to the vibrations (Gao *et al.* 2018). The magnitude of acceleration also differs depending on mounting location, e.g. with higher accelerations in the front wheel axle compared to the seat post (Olieman *et al.* 2012). At best, these approaches capture the condition of the surface in one track, and at worst at one spot on the surface. The cycle path surfaces can however be quite heterogeneous with regard to the roughness.

Condition assessments of roads include visually based subjective methods along with more advanced semi-automated systems with a varying degree of objective measurements. A Straight Edge (SE) could be used to measure the rut depth (Hoegh *et al.* 2010), while photos and videos of the road from cars (Lynch and Dutta 2010) or drones (Roberts *et al.* 2020) can detect surface distress. Laser profilometers on a car, which measure the shape and texture of the road surface is another way to effectively analyse road roughness (Laurent *et al.* 2012). The advantage of such a system, e.g. the Road Surface Tester (RST), is that it measures transverse- and longitudinal profiles as well as texture at high resolution, down to 1 mm between data points in transverse and longitudinal directions and an accuracy of 0.5 mm in depth (Laurent *et al.* 2012). The data obtained permits calculation of unevenness through the International Roughness Index (IRI), rut depth, crossfall, edge deformation, mega texture through Root Mean Square (RMS) (Durst *et al.* 2011), and macro texture through Mean Profile Depth (MPD). An advantage is that the measurements can be conducted in real-life traffic conditions without affecting other road users, and due to the high speeds at which the measuring can be conducted, measurements can be made over large distances in a short time. The downside of the system is that even though it is well adapted and highly useable for the roads, the size and required minimum speed of the vehicle (Sayers and Karamihas 1996) make it less suitable for cycle paths.

The MPD was primarily developed to measure the friction of the tyre-surface interface for cars. The IRI is even less applicable than MPD for measuring the cycle paths, as it has been developed to measure the comfort of car drivers (Thigpen

*et al.* 2015), and basically gives a value of the vertical displacement in a model of a quarter car with certain characteristics when moving along a road at a certain speed (Sayers *et al.* 1986). Hence there is a need for alternative metrics more adaptable to the perception and preferences of cyclists (Niska and Sjögren 2014, Chou *et al.* 2015). Some metrics, such as Dynamic Comfort Index (DCI) (Bíl *et al.* 2015), Evenness Coefficient (EC) (Gorski 1981) and 0.5 m Straight Edge ( $SE_{0.5}$ ) (Niska *et al.* 2011), have been suggested as more relevant options. The DCI – which ranges between 0 and 1, where high values identify the more comfortable roads with less vibration (Bíl *et al.* 2015) – uses acceleration data as input, whereas the rest of these metrics use the longitudinal profile data. The EC consists in creating a flattened version of the measured longitudinal profile through a sliding average. The EC value, which differs depending on the base length that is used to create it (Gorski 1981, Van Geem and Beaumesnil 2012), can be deduced from the area between the longitudinal profile and this flattened profile. In Belgium, where this method is commonly used, base lengths of 0.5 and 2.5 m should be applied for cycle paths (De Swaef 2019).

The effort of developing new metrics could be accompanied by developing new condition assessment methods that are more adapted to the conditions of cycle paths (Thigpen *et al.* 2015). Niska *et al.* (2011) used a smart car with laser profilometers to measure the longitudinal profiles of the surface in two tracks, then compared it to subjective evaluations by cyclists. They found that the best correlation to the cyclists' evaluation was to apply a 0.5 m imaginary SE to the obtained data, moving forward in 100 mm steps along the longitudinal profile. The downside to these trials was that due to a low sampling rate of the laser profilometers, wavelengths below 200 mm could not be captured, thus missing explanatory factors on cyclists' perceptions on the comfort that stems from the texture (Niska *et al.* 2011).

Therefore, a system based on a similar technique – but adapted to be used especially on cycle paths – is being developed at the Swedish National Road and Transport Research Institute (VTI). This system, the Bicycle Measurement Trailer (BMT), consists of an e-bike and an attached trailer equipped with measuring devices (see further description in section 2, Method). The idea is to perform measurements at normal cycling speeds, without interfering with the traffic or preventing other road users from accessing the cycle path. An advantage of the measuring system described in this paper is that it can measure an area corresponding to the whole width of the trailer while moving – and thus better capture any cracks or anomalies that the cyclists would normally avoid. A system that can assess more than the track of the cyclist her/himself is therefore believed to be beneficial for the precision of the condition assessment.

As described above, both the texture and the unevenness are believed to be of importance for cyclists' comfort when riding over a cycle path surface. The frequencies to which the human body is most susceptible, i.e. 4, 8, and 16 Hz (Mariunus *et al.* 2008, Wang and Easa 2016), lead to wavelengths of 1.25, 0.62 and 0.31 m respectively when considering an average cycle speed of 18 km/h (Dewanckele 2017). The speed range of the measurements in this study (10–33 km/h) tends to

indicate wavelengths of 0.17–2.26 m. Previous work suggests that it is roughness – with wavelengths ranging from about 5 mm up to 5 m – that will affect this comfort (Niska *et al.* 2011). The roughness corresponding to such wavelengths is found within the macro texture spectrum (0.5–50 mm), e.g. protruding aggregates or cracks, and mega texture spectrum (50–500 mm), e.g. potholes and smaller bumps, along with smaller areas of unevenness (0.5–5 m) such as larger bumps or settlements on restored pavement sections. A method that can cover both the texture and unevenness is therefore of great importance for cycle path surfaces and will be presented in the following.

The purpose of this study is to develop and assess a method that can objectively measure cycle path surface texture and unevenness and can relate these to the perceived comfort of cyclists. The collected data should be adequate for the calculation of relevant metrics and the system should be easy to operate.

## 2. Materials and methods

To study the accuracy and reliability of the proposed method in this paper, and its capacity to measure relevant metrics to reflect the cyclists' perception of comfort, the texture and unevenness of some commonly used surface types on cycle paths was assessed with the BMT developed at VTI.

### 2.1. The bicycle measurement trailer

The BMT is designed to facilitate condition assessment and evaluate riding comfort on cycle paths. The general composition of the system consists of an e-bike with an attached trailer, equipped with devices to measure the texture and evenness of the cycle path surface. As the bicycle advances, the surface behind it is scanned by a line-laser that is mounted on a specially constructed frame attached to the handlebar of the trailer, as seen in Figure 1 (a). The height of each data point on each scanned transverse profile is determined by the reflected light of the laser. An accelerometer is attached on top of the mount. A laptop computer, a car battery powering the whole system, and a data acquisition device are located inside the trailer. The trailer and a list of its components are described in Table A1 and depicted graphically in Figure A1 in Appendix A. The cycle path that is to be measured is given a coordinate system, whereby the x-axis denotes the width, the y-axis denotes the longitudinal direction, and the z-axis denotes the vertical position of the cycle path surface in the corresponding x-y coordinate, as seen in Figure 1 (b).

The maximum resolution with the current configuration of the BMT is 0.5 mm for x, 1.2 mm for y and 0.25 mm for z, and the maximum possible width of the transverse profile is 542 mm.

### 2.2. Data collection

The data used for the analysis in this paper was retrieved from a field experiment conducted at the campus area of Linköping University, Sweden, between November 2021 and July 2022. The surfaces that were used for the measurements were a

gravel surface (G); a 290×137 mm small concrete block pavement (SCBP); an old cracked dense graded asphalt concrete (OCAC), an old uncracked dense grade asphalt concrete (OUAC), a new dense graded asphalt concrete (NAC); a workshop painted concrete floor (WF); a recently laid dense graded asphalt concrete (RLAC); and 425×850 mm big concrete block pavement (BCBP). The surfaces can be seen in Figure 2. G, SCBP and BCBP are the same surfaces that were used in a previous study by Niska and Sjögren (2014).

#### 2.2.1. Texture measurement

To determine the texture of the surface, sections of the eight different surfaces in Figure 2 were measured with the BMT, at a tyre pressure of 2.3 bars (33.4 PSI). First, the accelerometer and the wheel pulse transducer were calibrated. Before each measurement, the surface was checked for moisture and the exposure time was set to a suitable value depending on the perceived amount of moisture on the surface. The settings for the parameters used for each surface can be seen in Table B1 in Appendix B. With the exception of G, the surfaces of the sections were manually swept with a broom to get rid of any gravel, debris or other elements foreign to the surface itself that could potentially influence the measurement. The sections were then measured using a distance measuring wheel and marked out with road marking chalk. Reflexive plates to trigger the start and stop points of the BMT measurements were laid out on top of these markings. For G an alternative method had to be applied, which consisted of using wooden boards instead of the reflective plates. To have some references when cycling, a straight line between the start and stop points was also marked with longitudinal markings every metre.

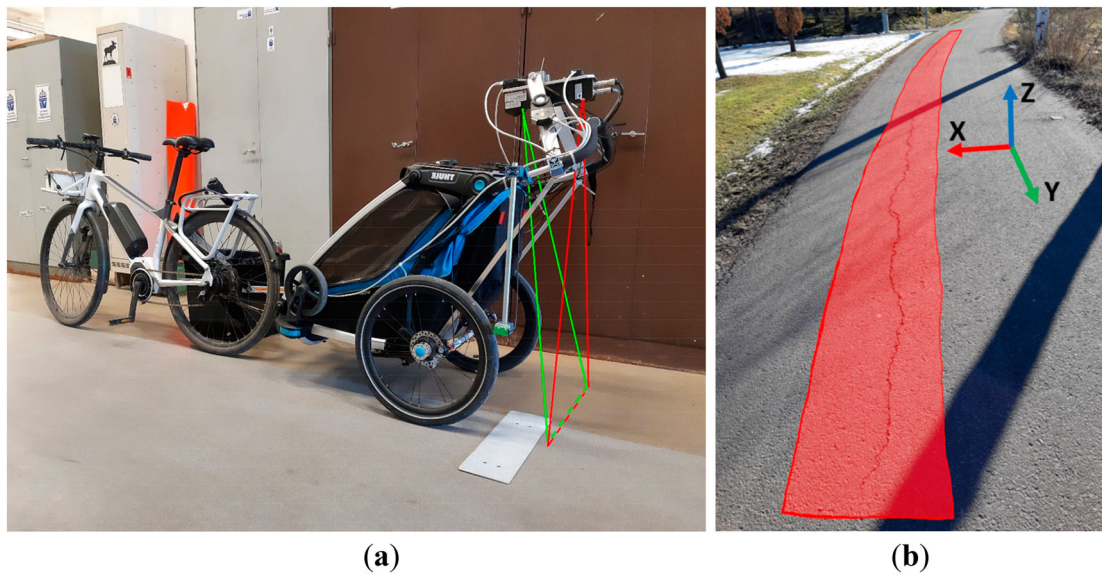
Measurement began by starting some 20 metres before the start plate, gaining sufficient speed to maintain a good manoeuvrability of the bicycle with as little swaying as possible. The operator then tried to maintain the course on the marked longitudinal line, along with an even speed throughout the measurement, to minimise potential vertical and lateral movements of the BMT. The speed was registered when passing the start plate, in the middle of the measuring distance, and again when passing the stop plate.

#### 2.2.2. Unevenness measurement

To determine the unevenness, i.e. the longitudinal profile, four surfaces were chosen: SCBP, OUAC, RLAC and BCBP, see Figure 2.

First, some measurements were conducted to control the accuracy and the sensitivity of the system. The OUAC was used for these tests. The verges of the cycle path were cleared of any disturbing vegetation, and the surface was brushed. A stretch of 125 m was measured with a measuring wheel and the start and stop positions were marked with reflective tape. The surface was measured with an RST car in three repetitions at a speed of 30 km/h. The same surface was then measured with the BMT at four different settings. First, the distance was measured five times at 'normal' cycling speed (19–24 km/h). Then three repetitions were conducted at high cycling speed (30–33 km/h), followed by three repetitions at normal speed (19–23 km/h) but where a conscious lateral swaying motion of the BMT was applied. Finally, two



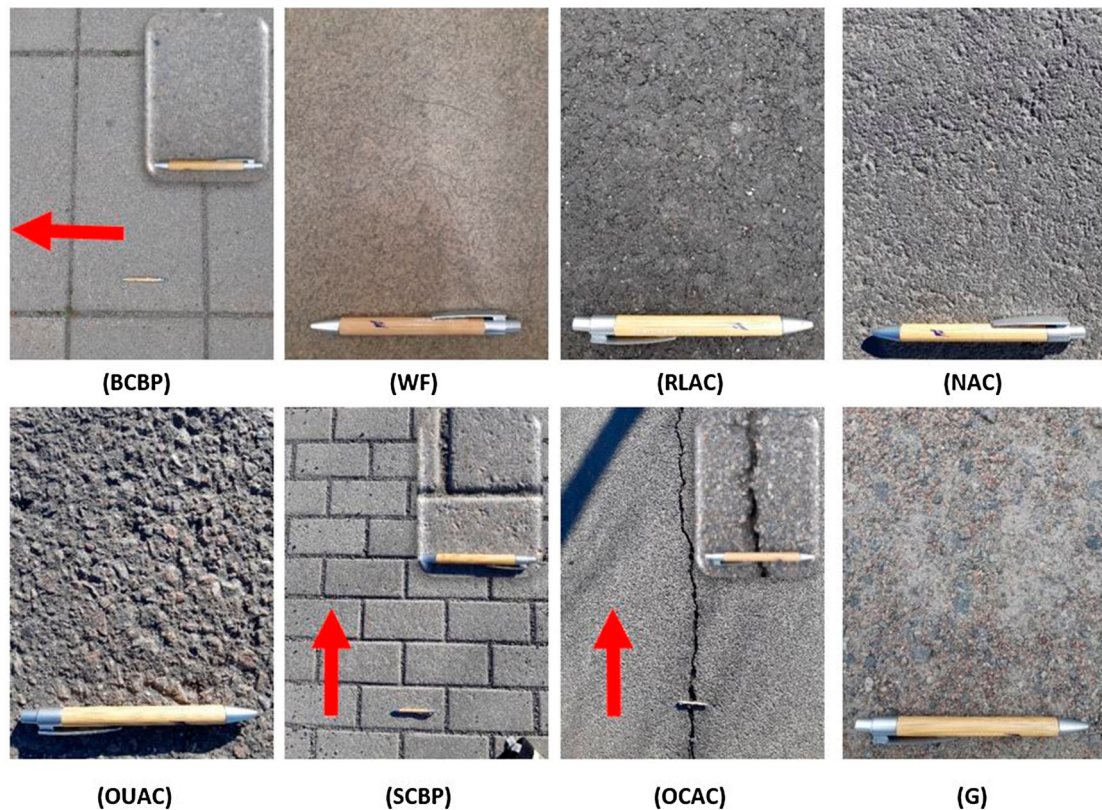


**Figure 1.** (a) The BMT: red lines indicate laser emission, green lines indicate the reflected light. (b) Representation of the laser scanned area. The red, green and blue arrows indicate the coordinate system for the measurements.

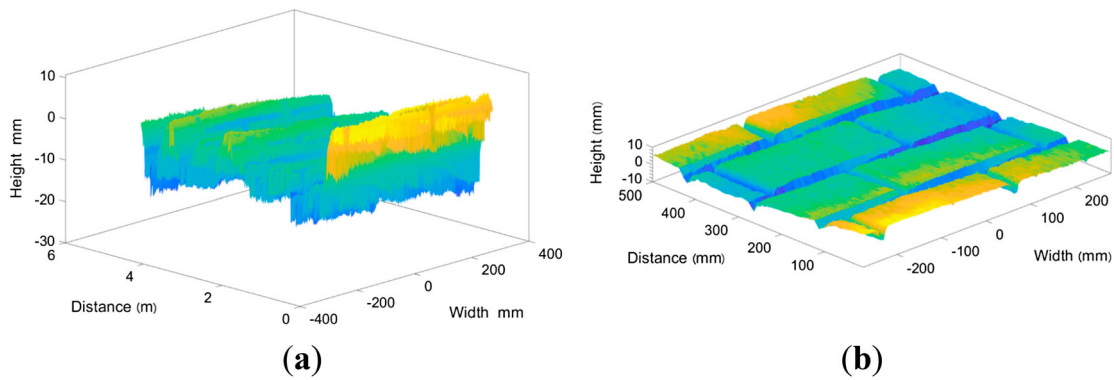
repetitions were conducted at low cycling speed (10–12 km/h). For these measurements a resolution of 0.5 mm between  $x$ -coordinates and 10 mm between  $y$ -coordinates was used.

After the control runs, the three remaining surfaces, **RLAC**, **SCBP** and **BCBP**, were measured at normal cycling speed (about 20 km/h) with the same  $x$ - and  $y$  resolutions as the

control runs. Each surface was measured five times. The settings for the parameters can be seen in [Table B1](#) in Appendix B. In order to be compared to the RST data, the mean for every 100 mm in the longitudinal direction and the mean of a 100 mm bundle of the centre of the transverse profiles are used for the BMT.



**Figure 2.** The measured surfaces: **BCBP** big concrete block pavements; **WF** painted concrete workshop floor; **RLAC** recently laid dense graded AC; **NAC** new dense graded AC; **OUAC** old uncracked dense graded AC; **SCBP** small concrete block pavement; **OCAC** old cracked dense graded AC; and **G** gravel. Arrows indicate the cycling direction. For the **BCBP**, **SCBP**, and **OCAC**, a close-up of the texture has been inserted in the upper-right corner.



**Figure 3.** The figure shows (a) the raw data from the BMT measurements on the **SCBP** and (b) data from the same surface with accelerometer data compensation to remove the movements of the BMT. Note that the scales on the axes are different in (a) and (b). Yellow indicates positive z values and blue indicates negative z values.

### 2.3. Data analysis

The laser scanning of the surface consists of several transverse profiles, each of which is composed of several data points which must be bound together to form longitudinal profiles for each measuring point on the transverse profiles to create the representation of a surface. The vertical movements of the BMT are compensated with the accelerometer data, and the horizontal transverse movements of the BMT are removed from the data using the MATLAB detrend command. The difference between a direct representation of the raw data and the same data after the compensation can be seen in **Figure 3**, in this case for the **SCBP**.

To describe the texture of the surface, the RMS was calculated for each transverse profile ( $RMS_{TR}$ ) of the eight different surfaces: **G**, **OCAC**, **OUAC**, **NAC**, **RLAC**, **WF**, **SCBP** and **BCBP**. For the unevenness of the surface, first the accuracy was tested by comparing the mean z value for each y-coordinate of the BMT measurements for each setting, i.e. speed and lateral movement, to the mean z value for each y-coordinate of the RST. Then the repeatability of individual runs for each setting with the BMT was controlled against the mean of the RST, which has a high repeatability between individual runs ( $R^2 > 0.99$ ).

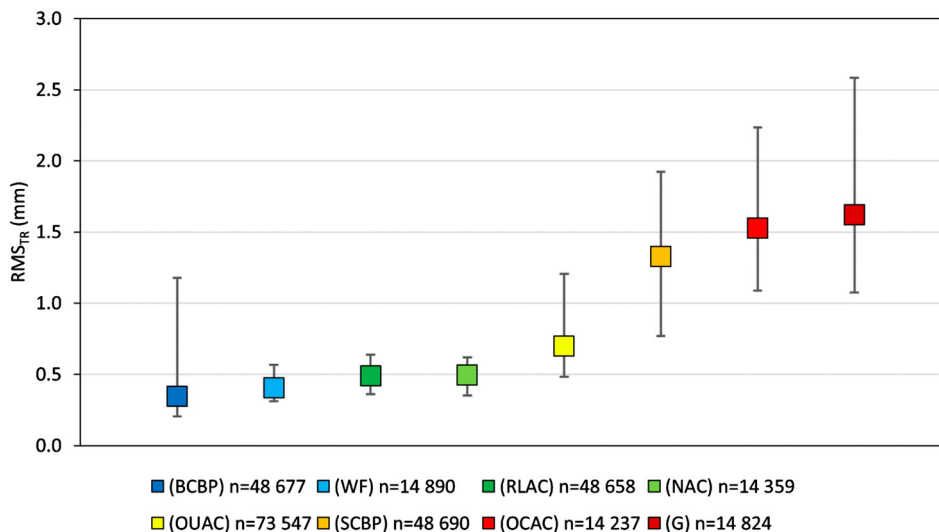
Next, the four different surfaces **RLAC**, **OUAC**, **SCBP** and **BCBP** were compared through a Power Spectral Density (PSD) analysis, where a PSD function, constructed through a Fast Fourier Transformation (FFT) of the collected data, shows how variance is distributed over wave number (Sayers and Karamihas 1998).

Finally, five different metrics that have been suggested in previous studies, or that are commonly used for evaluating the evenness of road surfaces – DCI, IRI, EC, SE and RMS – were calculated from the collected data on these four surfaces.

## 3. Results

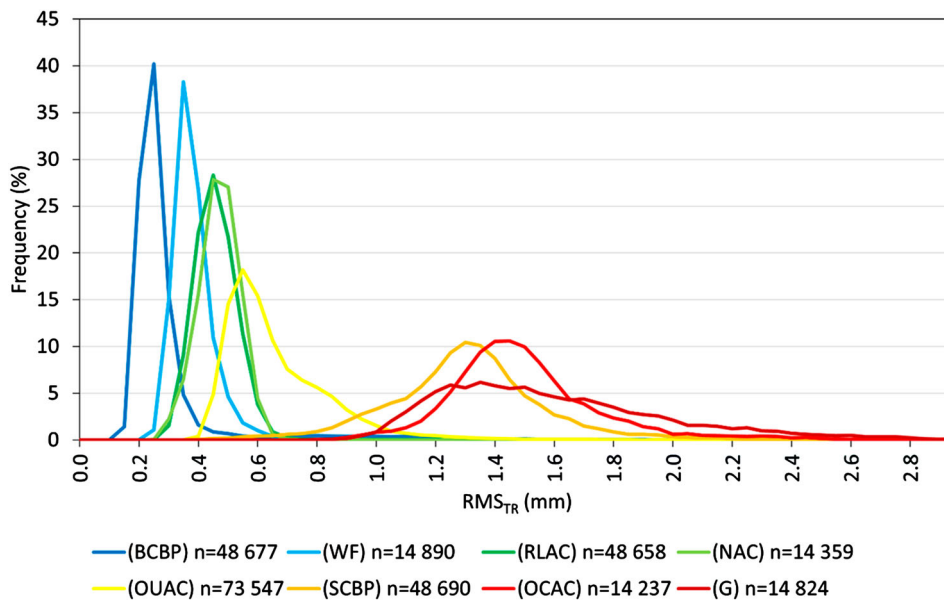
### 3.1. Texture of the surface

The  $RMS_{TR}$  for the different surfaces suggests a difference in texture between them (**Figure 4**). The smoothest surface seems to be **BCBP**, when considering the mean  $RMS_{TR}$  values. It is closely followed by **WF**, **RLAC**, **NAC** and **OUAC**. The differences between these five surfaces are small, and they are notably smoother than the rest of the surfaces, with mean  $RMS_{TR}$  values of approximately 0.34–0.70 mm. **BCBP** and **OUAC** differ from the  $RMS_{TR}$  values of the other surfaces



**Figure 4.** The different surfaces with respect to  $RMS_{TR}$  values. Boxes represent the mean average  $RMS_{TR}$  value for each surface, and whiskers the 2.5th and 97.5th percentile of the  $RMS_{TR}$  values. The n denotes the number of transverse profiles used for each calculation.





**Figure 5.** The distribution of  $RMS_{TR}$  values for the different surfaces.  $n$  = number of transverse profiles that compose the  $RMS_{TR}$  for each surface.

in this group in that the span between the mean and the 97.5th percentile, i.e. the upper whisker, is large, as opposed to the small span between the whiskers in relation to the mean  $RMS_{TR}$  for the other surfaces in the group.

The **G** surface has the highest mean  $RMS_{TR}$  of 1.62 mm, and the span between the 2.5th and 97.5th percentiles is also larger than for any of the other surfaces; this is interpreted as a more non-uniform texture than for the rest of the surfaces. **OCAC** and **SCBP** are quite close with respect to mean  $RMS_{TR}$ , with values of 1.53 and 1.33 mm respectively, and therefore it is possible to interpret these three surfaces as a group.

There are no statistically significant differences in mean  $RMS_{TR}$  between **G**, **OCAC**, **SCBP** and **OUAC** at 5% significance level ( $\alpha = 0.05$ ). Nor is there any statistically significant difference between **NAC**, **RLAC**, **WF**, **BCBP** and **OUAC**. Due to the large span of the upper whisker on **BCBP**, there is no statistically significant difference between this surface and **G**, **OCAC**, **SCBP** and **OUAC**. However, the mean  $RMS_{TR}$  values for **NAC**, **RLAC** and **WF** are statistically significant different from those of **G**, **OCAC**, and **SCBP**.

To get a better picture of how the  $RMS_{TR}$  values from the different transverse profiles are distributed, they can be plotted against the frequency at which they occur. **Figure 5** shows such a plot where the  $RMS_{TR}$  values have been arranged at intervals of 0.05 mm.

The surfaces that showed low mean  $RMS_{TR}$  values in **Figure 4**, i.e. **BCBP**, **WF**, **RLAC**, **NAC** and **OUAC**, all have a similar spike-like appearance. For **BCBP** the main mass of the  $RMS_{TR}$  values is at a low level. This shows that even though no statistically significant difference at 5% significance level ( $\alpha = 0.05$ ) was found between **BCBP** and the surfaces **SCBP**, **OCAC** and **G**, this difference could be demonstrated at slightly higher significance levels ( $\alpha = 0.094$ ,  $\alpha = 0.06$  and  $\alpha = 0.062$  respectively). By the same reasoning, at slightly higher significance levels it could be demonstrated that there is a difference between **OUAC** and the surfaces **SCBP** ( $\alpha = 0.16$ ), **OCAC** ( $\alpha = 0.068$ ) and **G** ( $\alpha = 0.076$ ).

### 3.2. Unevenness of the surface

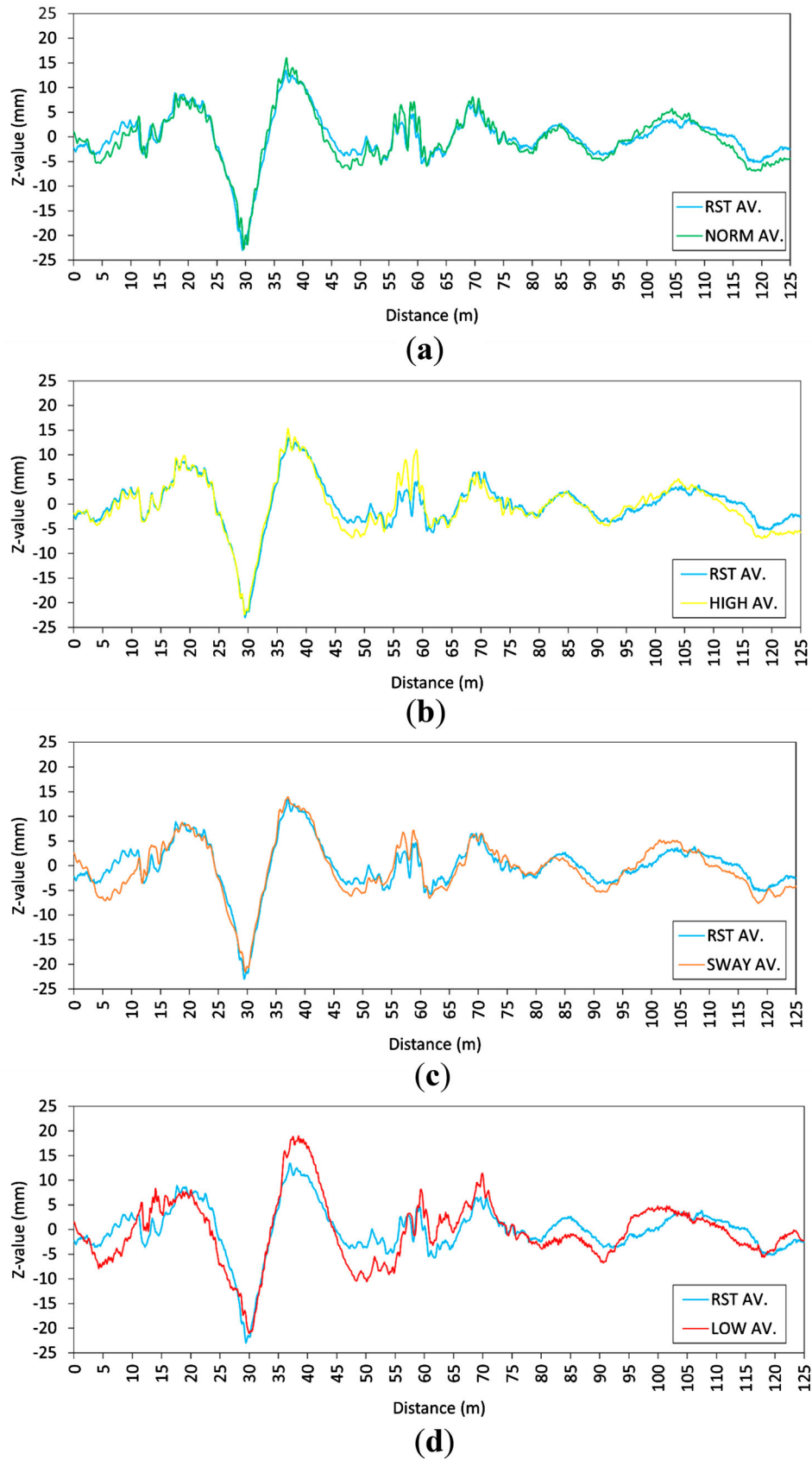
The unevenness of the surface is measured in the direction that the cyclists move, i.e. the longitudinal direction. The BMT measurements for **OUAC** and the corresponding RST measurements have been plotted as longitudinal profiles in **Figure 6**.

As can be seen from **Figure 6**, the BMT longitudinal profile measured at normal cycling speed (19–24 km/h) seems to be more consistent with the profile measured by the RST than the profiles measured at high (30–33 km/h) and low (10–12 km/h) cycling speeds – especially the latter. This seems to be true for the measurement whereby a lateral swaying motion of the BMT was also applied, which again was conducted within the range of normal cycling speed (19–23 km/h). For instance, the highest discrepancy in  $z$  values between the profile of the BMT and that of the RST for a particular  $y$  coordinate is 4.7 mm for the normal cycling speed profile, 7.9 mm for the high cycling speed profile, 8.8 mm for the low cycling speed profile, and 6.8 mm for the swaying profile. The shape of the profile seems to be consistent with visual observations on site, e.g. it was noted that a drainage pipe was located under the cycle path at the precise location of the downwards dip in the longitudinal profile at about 30 m. This would indicate that this is a natural low point where the collection of runoff water would be anticipated.

To illustrate how well the longitudinal profiles for the BMT match the profile of the RST, the mean  $z$ -coordinate for every  $y$ -coordinate of the different settings was plotted, see **Figure 7**.

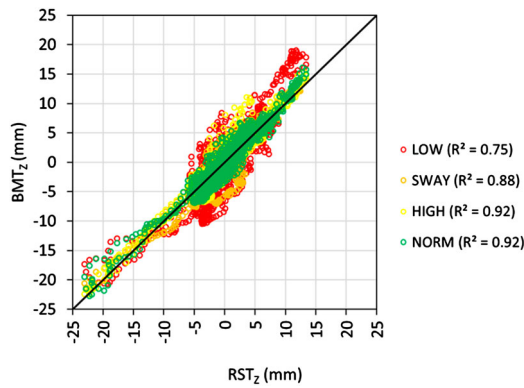
As the figure shows, the profile that best corresponds to the RST is that for the measurements conducted at normal cycling speed ( $R^2 = 0.92$ ), closely followed by the measurements at high cycling speed ( $R^2 = 0.92$ ). The third best fit is the measurement with a swaying lateral movement ( $R^2 = 0.88$ ), while the data points in the measurement at low cycling speed are those that least correspond to the RST ( $R^2 = 0.75$ ).

It is important to find out which setting best corresponds with the RST longitudinal profile as it can say something



**Figure 6.** Longitudinal profiles from measurements with the RST (blue line) and the BMT (green, yellow, orange, and red lines) at (a) normal cycling speed, (b) high cycling speed, (c) normal cycling speed with a lateral swaying movement, and (d) low cycling speed.





**Figure 7.** The z-coordinates for each y-coordinate measured with the BMT compared to the measurements from the RST.

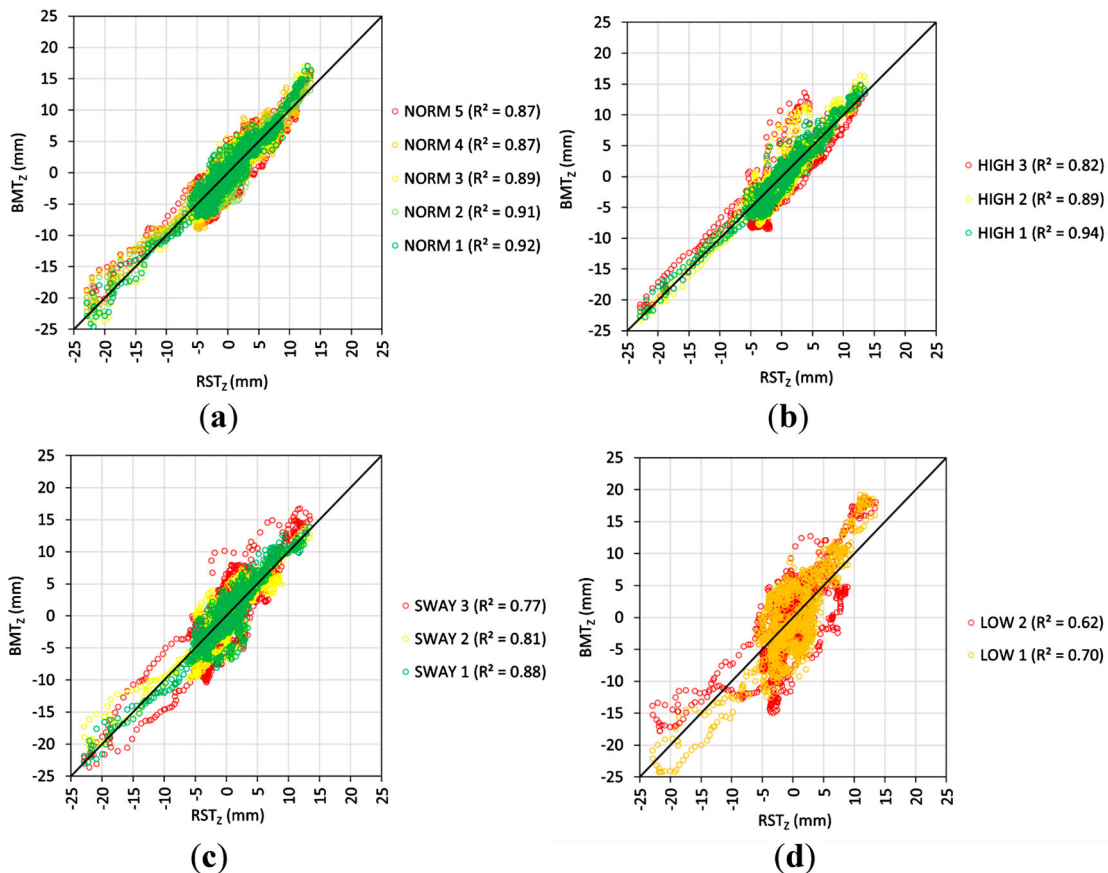
about the accuracy of the system and the sensitivity to different conditions of measurement. Equally important, however, is the repeatability of the system. Data for every single repetition of each setting is therefore plotted in **Figure 8**.

Not only do the normal cycling speeds seem to be more accurate with respect to the RST, but they also seem to have better repeatability ( $R^2 = 0.87$  to  $0.92$ ) than the other settings, even though they were measured five times as opposed to three times for the high cycling speed ( $R^2 = 0.82$  to  $0.94$ ) and the swaying motions ( $R^2 = 0.77$  to  $0.88$ ), and twice for the low cycling speed ( $R^2 = 0.62$  to  $0.7$ ). The fact that the individual

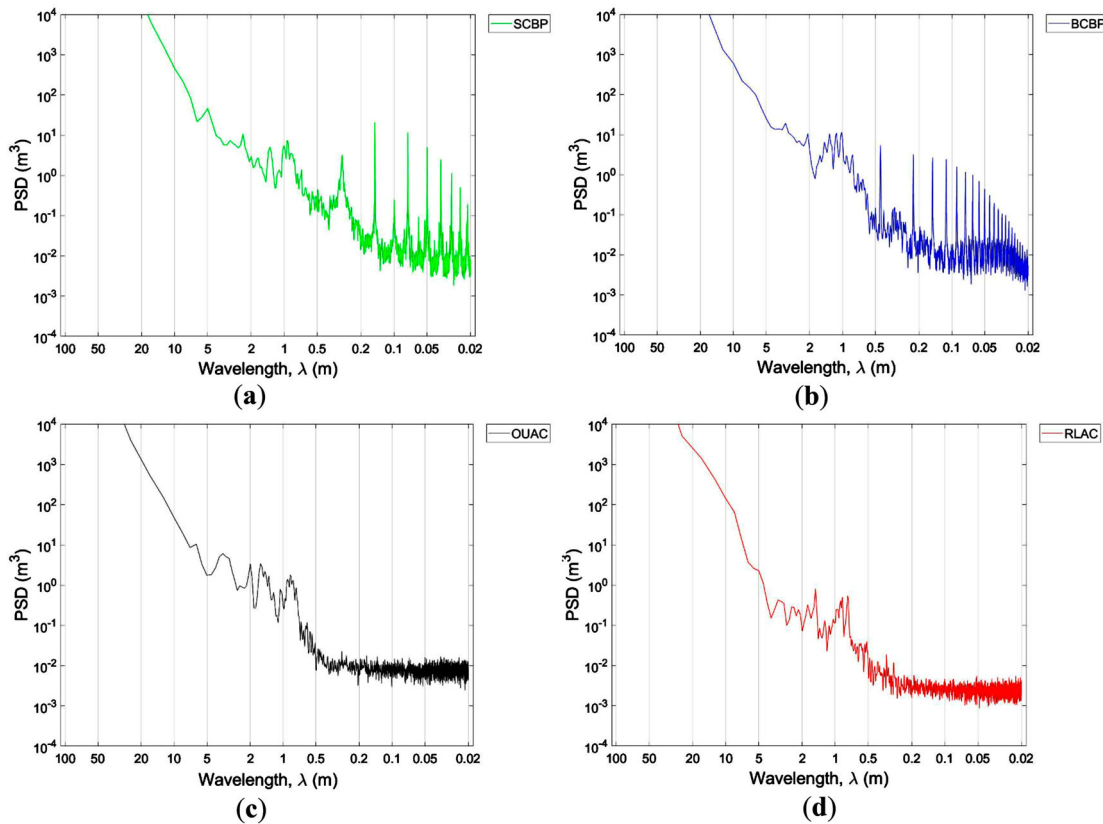
repetition of the BMT that best corresponds with the RST belongs to the high cycling speed ( $R^2 = 0.94$ ), along with the fact that the  $R^2$  values for the second-best repetition of the high cycling speed are on the same level as several of the repetitions for normal cycling speed, indicate that the system is more sensitive to low cycling speeds than high cycling speeds.

To evaluate the unevenness of the four different surfaces **OUAC**, **SCBP**, **RLAC** and **BCBP**, a PSD function for each surface was plotted (**Figure 9**).

The PSD for **RLAC** is lower than the rest of the surfaces for basically all wavelengths up to 5 m, which indicates that this is the smoothest and most even surface in the longitudinal direction. **OUAC** shows a similar curve but with PSD at a higher level, almost as if it was a parallel offset to **RLAC**. **SCBP** is the curve with the highest PSD values for the wavelengths, up to about 1 m. **BCBP** starts to have higher PSD values from wavelengths 1 m up to 5 metres, but it lies below the **SCBP** curve for wavelengths lower than 1 m. Especially for the smallest wavelengths in figures (b) and (c) (0.02–0.03 m), **BCBP** seems to have smaller PSD values than **OUAC**. This is in the macro texture domain, i.e. wavelengths between 0.5 and 50 mm. If the peaks for wavelengths below 0.15 m for **SCBP** and below 0.45 m for **BCBP** – which are the result of irrelevant overtones from the FFT – are not taken into account, there is not much difference in PSD values between these surfaces and the **OUAC** for wavelengths up to about 0.15 m. The peaks at 0.15 m for **SCBP** and at 0.45 m for **BCBP** are however real,



**Figure 8.** The z-coordinates for each y-coordinate per run for (a) normal cycling speed, (b) high cycling speed, (c) swaying lateral movements, and (d) low cycling speed, plotted against the z values for the mean average RST longitudinal profile.



**Figure 9.** PSD diagram for (a) SCBP, (b) BCBP, (c) OUAC and (d) RLAC. Note that the peaks for (a) up to the wavelength of 0.1 m are an effect of the FFT and do not reflect the PSD for these wavelengths. The same is valid for the peaks in (b) for wavelengths up to 0.4 m.

and they correspond to the closest calculated wavelength for the size of the different blocks of these concrete block pavements, which for **SCBP** are 137 mm and for **BCBP** is 425 mm. In other words, it is the joints between individual blocks of these surfaces that are reflected in these peaks.

To further validate the collected data, some of the metrics that have been suggested in the literature, and which are described in the Introduction, have been calculated. For the DCI, accelerometer data has been used, while the longitudinal profile data has been used for the remaining measurements. The results of the calculations are presented in Table 1. For the RMS the lengths 0.2 and 2 m have been used, as these are values that represent the theoretical wavelength span to which the cyclists are likely to be sensible for the cycling speeds in this study (10–33 km/h). The metrics are presented as mean values, based on the number of observations for each metric, e.g. for the IRI a value is calculated for every metre of the measured cycle path and thus the mean value is calculated

from  $n = 100$ . Relevant extreme values, i.e. least even spots, have been added to get an idea of the data spread.

The first thing to note is that the DCI values differ considerably from those calculated by Bíl *et al.* (2015) in the original study on DCI, even though some of the surfaces included in that study are believed to be similar to the surfaces in this study, i.e. ‘asphalt’, ‘worn asphalt’ and ‘interlocking concrete pavement’. The difference was that Bíl *et al.* (2015) found that mean DCI values for these surfaces ranged from 0.81 for the ‘asphalt’ and 0.73 for the ‘worn asphalt’ to 0.71 for the ‘interlocking concrete pavement’ and 0.60 for the ‘uneven interlocking concrete pavement’, whereas in this study the values are about ten times lower. This is probably due to the mounting of the accelerometer – in our case on the handlebar of the trailer.

The IRI seems to correctly differentiate **RLAC** and **OUAC** from **BCBP** and **SCBP**, but **RLAC** is shown to be more uneven than **OUAC** and **BCBP** is more uneven than **SCBP** – which is counterintuitive to what is perceived by cyclists. In other words, the statement that IRI does not capture the perceived comfort of the cyclists seems to hold true for this study as well.

The  $EC_{0.5}$  seems to not only detect the difference between the different surfaces, but also arrange them in the order that the cyclists from previous studies (Niska and Sjögren 2014, Bíl *et al.* 2015) rated these types of surfaces. The  $EC_{2.5}$  arranges the surfaces in the same order as the DCI min and the  $SE_{0.5}$  mean.

The  $SE_{0.5}$ , even though being estimated by Niska *et al.* (2011) as the length of SE with the best match to the cyclists’ evaluation, does not seem to comply with respect to the

**Table 1.** Calculated cycle path metrics for the four surfaces where the longitudinal profiles were measured.

Surface	DCI mean/ min	IRI mean/ max (mm/ m)	$EC_{0.5}/EC_{2.5}$ mean ( $10^3\text{mm}^2/\text{hm}$ )	$SE_{0.5}$ mean/ max (mm)	$RMS_{0.2}/$ $RMS_2$ mean (mm)
RLAC	0.084/0.081	3.17/12.73	0.74/25.63	5.37/16.09	5.42/5.68
OUAC	0.082/0.071	3.10/13.32	2.10/31.12	7.59/26.53	4.54/4.73
BCBP	0.066/0.046	6.47/21.51	7.11/64.34	15.46/28.82	8.71/9.16
SCBP	0.064/0.056	5.58/17.65	8.99/54.47	14.72/23.53	7.89/8.15

different surfaces included in this study. The mean for **BCBP** exceeds that of **SCBP**, which is inconsistent with the cyclists' perception of those particular surfaces (Niska and Sjögren 2014). The maximum  $SE_{0.5}$  value, for each 5 m interval is also higher for **BCBP** than for **SCBP** in general, so it is not a case of one extreme value affecting the mean value.

The RMS ranks **OUAC** as the most even surface, followed by **RLAC**, **SCBP** and finally **BCBP**. This is the same order that the surfaces were ranked by IRI but differs from the order of the rest of the metrics.

## 4. Discussion

### 4.1. Texture of the surface

The BMT is presented as an alternative to profilometer measurements with the RST on cycle paths. However, the BMT cannot compete with the RST when it comes to accuracy. For example, the resolution of data achieved with the BMT at its current configuration is not enough to calculate MPD values according to the ISO standard 13473-1 (2019). Therefore, in this study  $RMS_{TR}$  values have been calculated – based on the transverse profiles and sampled with 0.5 mm resolution – to compare the different surfaces with respect to texture.

The different surfaces are clearly distinguishable with respect to  $RMS_{TR}$  values. In general, they are ranked in the order that intuitively seems reasonable. **WF** is expected to be the smoothest surface, but when only looking at the mean value **BCBP** is even smoother, as the concrete blocks in themselves are quite smooth. It is not surprising to find that **RLAC** is one of the smoothest surfaces, but it was not expected to be as similar to **WF** as it actually is. The operators are of the impression that even though it basically has the same average  $RMS_{TR}$  value as **SCBP**, **G** feels more comfortable. This is in line with the results of Niska and Sjögren (2014) where the participants stated **G** to be more comfortable than **SCBP**, even though **G** resulted in higher acceleration values. Apart from the operators, there were no test subjects for this study and the operators might be biased as they knew the results of the previous study beforehand. Still, it seems as if there is something more that affects cyclists' perception of the surfaces than just the mean values of accelerations and  $RMS_{TR}$ . As there is a difference between vibration and shock produced by surfaces (Sjögren 2021), it could be the case that **G** causes more vibrations, while the joints between the blocks at **SCBP** cause unpleasant shocks, even though each block may be smooth in itself. These shocks are perhaps perceived as more uncomfortable than the vibrations caused by **G**. That would also explain why **SCBP** was ranked as more uncomfortable than **BCBP** in the former study. More studies with test cyclists, should be conducted, preferably in large numbers, where the preferences of cyclists with regard to vibration and shock are discerned.

### 4.2. Unevenness of the surface

IRI,  $SE_{0.5}$ , and RMS all show **BCBP** as the most uneven surface. That is not how the test cyclists in Niska and Sjögren (2014)

ranked this surface. It indicates that these metrics are capturing some aspect of the unevenness that is not perceived by the cyclists, and thus they seem less consistent with the subjective evaluation. For the IRI this lack of consistency is believed to be because it is influenced by wavelengths between 1.2 and 30.5 m, with a maximum sensitivity for the wavelengths 2.4 and 15.4 m (FHWA 2005). Many of the wavelengths that affect cyclists the most (<1.2 m) are therefore missed by this metric, at least for normal cycling speeds (18 km/h). The calculation intervals for the SE and RMS, on the other hand, have been chosen to detect the wavelengths that theoretically would affect the cyclists the most. However, these metrics seem to be unable to capture the effect of the shocks to which the cyclists are subjected when riding over the joints of a block pavement. The  $SE_{0.5}$  was proposed based on the evaluation of asphalt surfaces of different conditions (Niska *et al.* 2011). It might be that the metric is good at determining the comfort of asphalt surfaces, but less good at covering the aspects of the concrete block pavements where repeated shocks when riding over the joints occur. As seen from the texture measurements, the block pavements seem to be quite smooth – and hence quite comfortable – on top of each block, but the joints make the riding experience less comfortable. A similar reasoning could probably be applied to the RMS. Another aspect that might influence the values is that the  $RMS_{0.2}$  is based on 20 values and the  $RMS_2$  is based on 200 values, whereas the  $RMS_{TR}$  is based on 600–1000 values, depending on the x resolution that was used.

The difference in magnitude of the DCI values between this study and the original study that defined DCI (Bíl *et al.* 2015) might be interpreted as more uneven surfaces in general for this study. However, this is probably not the case but more likely it is related to the mounting of the accelerometer on the bicycle in the previous studies (front fork (Bíl *et al.* 2015) and handlebar (Niska and Sjögren 2014)) as opposed to mounting the accelerometer on an attached trailer. The practical implication of this is that the DCI is sensitive to the mounting position of the accelerometer, and when it is mounted on the BMT, the metric does not produce comparable DCI values.

For the  $EC_{0.5}$ , all the surfaces comply with the upper limit value of 15 (De Swaef 2019). However, only **RLAC** and **OUAC** comply with the  $EC_{2.5}$  upper limit value of 45 (De Swaef 2019), meaning that **SCBP** and **BCBP** are not appropriate materials for cycle path surfaces with respect to riding comfort.

The mean DCI and the  $EC_{0.5}$  rank the types of surfaces in the same order as the test cyclists from (Niska and Sjögren 2014) and (Bíl *et al.* 2015), indicating that these are useful metrics to describe the subjective comfort of cyclists. DCI minimum and  $EC_{2.5}$ , on the other hand, rank **BCBP** as the most uneven surface, as all the other metrics do, which indicates that there are some wavelength components that impact the results, but which perhaps are not perceived as uncomfortable by the cyclists. The EC has the advantage of using profile data, which is theoretically less sensitive to the conditions of the bicycle and rider than the acceleration measurements used for the DCI, even though it is suggested that the DCI is not sensitive to bicycle type and different accelerometers (Bíl *et al.* 2015).

Speed seems to have an impact on the results of the DCI (Bíl *et al.* 2015) as well as the results of the EC (Van Geem and Beaumesnil 2012). As a method of collecting data, the BMT also seems somewhat sensitive to speed, where the low speed (10–12 km/h) affected the accuracy of the measurements, while the high speed (30–33 km/h) barely seemed to have any impact. Thus, more research needs to be conducted to determine the sensitivity to the cycling speed on the measurements and how the calculations of the metrics are affected. All in all, the EC is considered to be the most relevant of the tested metrics, but more measurements on different surfaces, speed ranges and settings are advised.

## 5. Conclusions

Texture and unevenness tests on different surfaces have been conducted with a BMT and analysed with respect to relevant metrics to evaluate the accuracy and repeatability of the BMT. It can be concluded that the BMT has a high accuracy ( $R^2 = 0.92$ ) at normal and high cycling speeds (19–33 km/h) compared to the standardised road measuring system, RST. The accuracy, however, decreases ( $R^2 = 0.75$ ) with low cycling speed (10–12 km/h). The repeatability at normal cycling speed also seems to be high,  $\pm 3\%$  difference between repetitions, but decreases with high cycling speeds ( $\pm 7\%$ ) and low cycling speeds ( $\pm 6\%$ ). The recommendation, therefore, is to conduct more tests at different cycling speeds to determine limit values for acceptable accuracy and repeatability of the BMT.

The BMT manages to differentiate between surfaces with respect to pavement texture. The order of texture roughness for the surfaces complies with the perceived texture roughness by visual inspection. The eight surfaces could therefore be divided into two groups, where **BCBP**, **WF**, **RLAC**, **NAC**, and **OUAC** are smooth whereas **SCBP**, **OCAC**, and **G** are rougher. A similar argument can be made for the longitudinal evenness of the surfaces, where the calculations of the EC and the DCI not only rank the surfaces correctly, but also shows a considerable difference between the asphalt surfaces and the block pavements, which seems to reflect the cyclists' experiences. More measurements should be conducted on similar types of surfaces to be able to generalise these findings. Other cycle path surfaces such as cobble stones or other types of block pavements could also be assessed with the BMT, with respect to texture and unevenness to determine limit values for the comfort of cyclists.

With respect to the evaluated metrics for unevenness, the EC seems to give the best conformity to the rating that test cyclists have given to the same types of surfaces in previous studies. Further research on the BMT as a tool for condition assessments and cycling comfort should thus proceed from this metric.

In conclusion, the BMT seems to be a promising tool for condition assessments, but it needs further development to be used in practice, where the ability to measure longer sections at a time should be prioritised.

## Author contributions

Conceptualisation, M.L., A.N. and S.E.

Methodology, M.L., A.N., S.E. and P.A.

Validation, A.N. and S.E.

Formal analysis, M.L.

Investigation, M.L. and M.T.

Resources, A.N. and S.E.

Software: P.A. and M.T.

Data curation, M.L., M.T. and P.A.

Writing – original draft preparation, M.L.

Writing – review and editing, A.N. and S.E.

Visualisation, M.L., P.A. and M.T.

Supervision, A.N. and S.E.

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Funding acquisition, A.N. and S.E.

All authors have read and agreed to the submitted version of the manuscript.

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## Data availability

Data are available open access through the Creative Commons Attribution 4.0 International license at the following DOI 10.5281/zenodo.7412703

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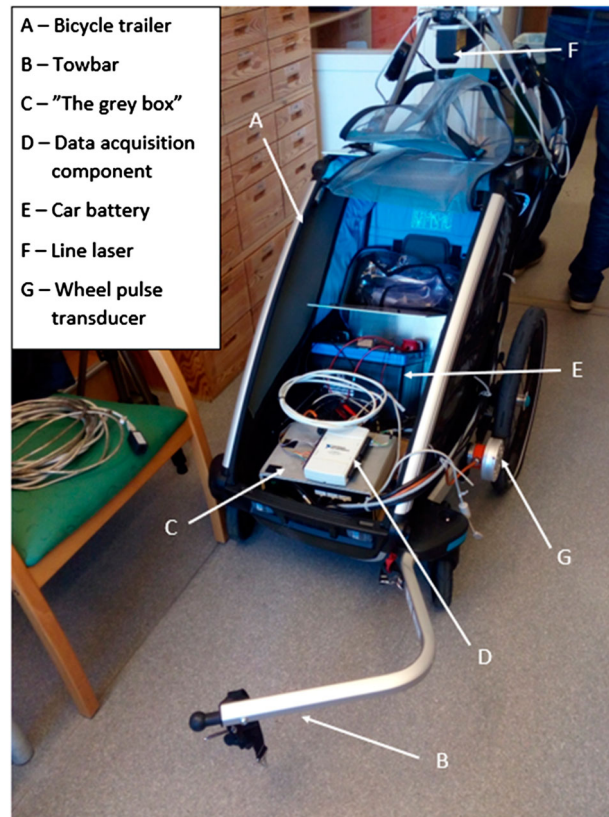
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## Appendices

### Appendix A

**Table A1.** The components of the BMT.

Component	Brand	Model
Bicycle trailer	Thule	Chariot Sport 1
Data acquisition component	National Instruments	USB 6212
Line laser	Gocator	2375
Wheel pulse transducer	Kübler	8.5020.2541.1250
Photoelectric reflective sensor	Seeka	GR2M SPN



**Figure A1.** The inside of the BMT, with the components that make up the system.

### Appendix B

**Table B1.** Settings for the conducted measurements with the BMT.

Surface	Repetitions	Distance (m)	Av. speed (km/h)	X-res. (mm)	Y-res. (mm)	Exposure time ( $\mu$ s)
RLAC	5	100	20	0.5	10	300
OUAC	5	125	20.7	0.5	10	300
BCBP	5	100	20	0.5	10	300
SCBP	5	100	20	0.5	10	300
WF	3	25	4	0.873	5	300
NAC	3	25	9.8	0.873	5	300
OUAC	5	125	20.7	0.5	10	300
OCAC	3	25	11.3	0.873	5	600
G	3	25	11.1	0.873	5	300