CHALMERS
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Condition of bicycle paths
The importance of full-width measurements

Master's thesis in Infrastructure and environmental engineering

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Master's Thesis ACEX30-19-35
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Examensarbete ACEX30-19-35
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Examiner: Professor Xiaobo Qu
Department of Architecture and Civil Engineering
Division of Geology and geotechnics
Urban Mobility Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone: + 46 (0)31-772 1000

Cover:
Measuring bicycle path outside VTI's office
in Linköping 16/4-2019
Picture photographed by Leif Sjögren, 2019
Department of Architecture and Civil Engineering
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ABSTRACT

In the strive to increase bicycling because of benefits for health and environment, the need for a standardised way to measure the surface roughness on bicycle paths has incurred. This kind of measurements have been performed on car roads since the fifties. Earlier studies suggest that the measurement methods for car roads are not suitable for measuring on bicycle paths. VTI, the Swedish national road and transport research institute has developed measurement instruments and methods suitable to use on bicycle paths.

This study is comparing two measurement methods with the goal to contribute to the research on how to measure unevenness on bicycle paths in the future. One method is to measure the unevenness through the response, by an accelerometer in a smart phone mounted on a bicycle and the other method is to measure the unevenness with a laser sensor based profilometer, mounted on a bicycle trolley. The reason why these measurement methods are compared is that the accelerometer measures in the wheel path where the bicycle is positioned contrary to the profilometer that measures the profile over a wider width.

Measurements with the accelerometer give an indication of the surface condition on a bicycle path, but the risk is that defects outside the bicycle's wheel path during the measurements will be missed. The risk is larger if there is a large variation in surface quality over the bicycle path width. Measurements with the profilometer give a more detailed picture over the path surface, but the measurement method with this device needs to be developed further and the purpose of measuring unevenness, will in the end, determine which method that is the most useful.

Keywords: Bicycle path, Bicyclists, Measurement, Safety, Comfort, Function, Maintenance, Width

Contents

Preface

The master thesis project is a significant part of a master’s degree where the students have to show that they can make use of the knowledge they acquired during their master studies. This report is the presentation of a master thesis project of 30 credits performed at Chalmers University of Technology during the spring of 2019 as a part of a master’s degree in Infrastructure and Environmental Engineering.

Research in the field of bicycle path condition regarding measurement methods is in an early stage compared to the standardised methods for car roads. With the increased use of the bicycle as a preferred transport mode, both the bicyclists and the road owners will benefit from the knowledge gained by this master thesis project. Further research will in the future lead to a better understanding of how bicyclists are affected by the bicycle path condition and a reliable way of measuring it.

The subject was assigned by VTI, and employees at VTI have provided guidance through the project. Supervisor at VTI was Leif Sjögren research director at the department of operation and maintenance. Thanks to Peter Andrén who prepared and transferred all the data from the application, Harry Sörensen who mounted and calibrated the measurement equipment and Thomas Lundberg who answered my questions on how to process the data from the profile measurements.

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Frida Olsson

Notations

Abbreviations

BLOS	Bicycle Level of Service
BPI	Bicycle Profile Index
EC	Coefficient of Evenness
GPR	Ground Penetration Radar
IP	Inertial Profiler
IRI	International Roughness Index
MPD	Mean Profile Depth
NVDB	National Road Database
PCI	Pavement Condition Index
PSD	Power Spectral Density
PSI	Present Serviceability Index
RMS	Root Mean Square
RST	Road Surface Tester
SAVER	Shock and Vibration Environment Recorder
SVA-value	Total Weighted Acceleration value (Summerat Viktat Accelerationsvärde)
VGU	Road and Street Design guidelines (Vägars och Gators Utformning)

Equations

$$International\ Roughness\ Index, IRI = \frac{1}{L}\int_0^{L/V} |\dot{z}_s - \dot{z}_u| dt \tag{2.1}$$

$$\text{Root Mean square}, RMS = \sqrt{\sum (X_i - \bar{X})^2} \tag{2.2}$$

$$Comfort\ value = (0.1 * SVA) + 1 \tag{2.3}$$

Definitions

Macrotexture -	irregularities varying from an idealised plane with dimensions in the range 0.5mm-50mm (SIS, 2019).
Mega texture -	irregularities varying from an idealised plane with dimensions in the range 50mm-0.5m (ISO, 2008).

1 Introduction

The knowledge about the negative environmental and social impacts caused by the transport sector has increased the strive to use more sustainable transport modes (Eriksson, 2009). The transport sector needs to decrease its emissions of carbon dioxide and harmful particles, noise pollution and congestion (Behrends, 2018). One part of the solution can be to decrease the distance travelled by car and make more people take the bicycle instead. The bicycle can be used for many types of travels like commuting to work, doing short errands or for recreational purposes. There are significant health benefits with increased bicycling in the society (Panis, 2011). The development of more bicycle types is also increasing (Jin, et.al., 2015). Based on the possible benefits of increased bicycling the municipalities in Sweden are more interested in maintaining and investing in bicycle infrastructure.

Sweden has 290 municipalities (Government offices of Sweden, 2019). Many of the municipalities have different regulations and methods for building and maintaining bicycle paths (Niska, 2006). Guidelines for measurements of the bicycle path condition are missing, which makes it hard to compare the standards and methods between municipalities. The road engineers employed by the municipalities do not have the time to develop and implement a national standard for measurements of bicycle paths. There are regulations about the condition of bicycle paths, but the current regulations are based on the regulation for car roads. These regulations are not adapted to represent how the bicyclists experience the path condition and the condition of bicycle paths are seldomly checked.

80% of bicycle accidents are single-vehicle accidents (Niska & Sjögren, 2007). According to studies in Umeå, many of the accidents, up to 50%, are related to the bicycle path condition. The number of accidents related to path condition can be even higher because the unrecorded number of accidents involving bicycles is high. For single vehicle accidents the loss is as high as 95% according to “Cykelplan Gävle” (Gävle municipality, 2010). When developing standards for measuring the condition of bicycle paths, many different aspects need to be addressed. The most important parameters for bicyclists and other path users are safety and accessibility. The research on what to measure on the bicycle path to represent the path condition is currently in process. Findings from this research have enlightened new questions, for example how and where to measure to make the measurements reliable and repeatable (Niska, 2006).

1.1 Background

The Swedish Transport Administration is responsible for a smaller part of the bicycle path network, while most bicycle paths are under the municipalities' responsibility. The municipalities usually follow the rules stated by the Swedish Transport Administration during the construction of bicycle paths, but for maintenance, they have their own regulation (Niska, 2006). The municipalities' budget affects the level of quality that the maintenance can reach. Some of the municipalities do all the maintenance work by themselves and others hire external contractors. The variation in quality over the road network can be due to that there are different stakeholders responsible for different path stretches. Measurements of maintenance and systematic control is a prerequisite to maintain a uniform standard on the bicycle network and to compare it between regions.

The functional requirements on the bicycle path condition in Sweden are based on those for car roads (Niska Sjögren & Gustafsson, 2011) and the most common way to monitor the condition of the bicycle paths is by visual inspections from a car (Niska, 2006). Those inspections often have a focus on technical quality instead of functional requirements as to safety and comfort for the bicyclists (Niska Sjögren & Gustafsson, 2011). The measurement methods have to represent the bicyclists' experience of the bicycle path condition and the functional requirements, not just the technical. Common causes of defects on the bicycle paths are overloading by heavy vehicles, frost heave, cracking, defect manholes, bad repairs and penetration by roots (Niska, 2011). The thin surface layer on bicycle paths is sensitive to mechanical loading.

It is important to perform preventive maintenance, because if the maintenance is lacking, small defects can become costly to repair (Niska Sjögren & Gustafsson, 2011). If the defects are noticed in time, they can be fixed before they pose a safety risk and avoid a high cost for the society. According to the municipalities, the hardest part of operation and maintenance is to maintain a high standard during winter and prevent unevenness in the surface (Niska, 2006). The cost for maintenance is often presented as the total sum, including both maintenance for car roads and bicycle paths and it is therefore hard to estimate the specific cost of maintenance on bicycle paths (Niska, 2011). The maintenance cost can also vary a lot from year to year depending on for example the weather conditions. The maintenance will be most effective if the bicycle path owner knows a lot about the bicycle path network and puts effort into planning the maintenance.

1.1.1 Bicyclists

Most municipalities have a system to receive and process the incoming information from the public bicycle path users (Niska, 2006). The municipalities let the public report defects on the bicycle paths and see this as a good way to get information about the path condition. The most common complaints about the bicycle path condition are glass debries and slippery path surface. Slippery path surface can be due to snow and ice or sand and gravel on the bicycle paths (Niska, 2011). Slip accidents are more common on separated bicycle paths. More women than men consider the risk of slipping a reason to not use the bicycle, it is also more women than men in slip accident statistics. To avoid the risk of slipping, maintenance should be prioritised in curves and slopes and sand and gravel should be removed from the bicycle paths after the winter (Niska, 2011). During the winter it is important to inform the bicyclists about the paths' condition. The requirements for snow clearance are stated from when the snowing stops, which makes it problematic for bicyclists to use the bicycle during a heavy snowfall.

Bicyclists prefer to have the bicycle path separated from the car roads and asphalt is the preferred surface layer according to bicyclists (Niska, 2011). Many bicycle paths in Sweden are a shared path between pedestrians and bicyclists, which can decrease the accessibility for the bicyclists (Niska & Sjögren, 2007). The comfort perceived by the bicyclists includes other parameters such as bushes and trees close to the path and lighting. Darkness makes the bicyclists feel uncomfortable and it makes it harder to discover obstacles (Zhao & Fang, 2016). The evenness of the bicycle path is of great importance and potholes affect the safety on the bicycle path a lot (Niska Sjögren & Gustafsson, 2011). Unevenness in the wavelength of 5mm-500mm is the most uncomfortable for bicyclists (Niska & Sjögren, 2014).

1.1.2 Maintenance

Problems with bicycle paths' condition relevant for the bicyclists' comfort can according to several studies correlate with friction, unevenness, structure and inclination (Niska & Sjögren, 2007). These parameters are related to the type of paving, weather conditions, surface damages like cracks or potholes and path design. Better quality of the bicycle paths will encourage more people to choose the bicycle (Niska, 2011). Access and comfort are functions that affect the number of people that choose to use the bicycle as a transport mode (Niska, 2011). Unevenness in the wavelength mega-texture and singular larger deformations is considered uncomfortable to pass, see Table 1.1. The time ratio between taking the bicycle or the car has to be low for people to choose the bicycle, preferably below 1.5. Improvements of the bicycle network have an undefined effect on the number of bicyclists and benefits for society. Investigations of reduced cost for the society when a measure is implemented are important in order to convince the stakeholders to finance bicycle projects. The cost for society with a bad condition on the infrastructure is higher than the maintenance cost according to Koglin & Varhelyi, 2018.

Table 1.1 Pavement surface texture (Li, et.al., 2013).

Unevenness	Wavelength
Megatexture	50mm - 500mm
Macrotexture	0.5mm - 50mm
Microtexture	< 0.5mm

In the local maintenance plans, the bicycle paths are often prioritised over car roads (Niska, 2006). There is a difference in the road owners' opinion about the bicycle paths condition and the condition perceived by the road users (Niska, 2011). Standards are based on experience rather than measurable parameters. The bicyclists do not feel prioritised by the road owners even if the road owners say they prioritise bicycle paths over car roads. To determine where and what maintenance that is needed to be performed on the bicycle path network, an effective and reliable way of measuring the current path condition is required (Niska & Sjögren, 2007). Bicyclists' opinions and perception of the bicycle path condition should be covered by a standardised method (Niska Sjögren & Gustafsson, 2011). An objective measuring method will help the stakeholders to motivate financing improvement of the bicycle network and decide where the largest need for maintenance is required. If the measurement method is standardised it is also possible to compare different parts of the network and evaluate degradation or the effect of improvement measures (Niska & Sjögren, 2007). With a standardised measurement method, the stakeholder can verify that the path complies to the regulations and guidelines. If a measure is implemented it should be possible to verify the effect of that measure to see if it has contributed to improved comfort and safety for the bicyclists (Niska, 2011). Standards for maintenance should be stated with clear formulations and measurable results, based on the quality that is required by the bicyclists.

1.1.3 Measurements

The measurements to determine the condition of car roads are based on international standards with both visual methods and standardised measurement instruments. For bicycle paths, this kind of investigation methods is not yet developed. To develop a reliable and repeatable measurement method, research has been carried out to determine what should be measured, whether the vertical acceleration is representative for the bicycle path condition or not and how the bicyclists' comfort and safety are related to the surface roughness (Niska & Sjögren, 2014). VTI, the Swedish National Road and Transport Research Institute are continuing the research by developing an instrument to measure the condition on bicycle paths. The measurement instrument consists of measurement equipment mounted on a bicycle carriage. Other measurements done by devices mounted directly on the bicycle and with hand driven equipment have already been carried out, but those only cover a small track of the path width. The width of older bicycle paths in Sweden are not registered and therefore in many cases unknown (Niska & Sjögren, 2007). Different widths of the bicycle path can be a problem when standardised measurements should be developed, because the wheel path might differ a lot between different stretches.

According to Leif Sjögren, VTI has been asked to measure the width of existing bicycle paths. Other aspects, for example, light and inclination could possibly be measured at the same time as the bicycle path condition. Potential problems with measurements on bicycle paths can be narrow path width, bad visibility due to curves or darkness and stops required during the measurement (Niska Sjögren & Gustafsson, 2011). Another question is how to present the information and whether or not it can be implemented in existing databases of information about the road network like GEOSECMA, PMSV3 or NVDB used by the municipalities in Sweden (Niska & Sjögren, 2007). In the future, bicycle paths will be measured with objective and reliable measurement methods similar to the ones used for car roads. To achieve this, it is important to investigate what the bicyclists and road owners want to know about the bicycle path condition. The aim of measuring the bicycle path condition differs if the structural or functional condition is observed. The structural condition includes evenness and bearing capacity and the functional condition is more related to the bicyclists' comfort (Niska, 2011).

1.2 Aim and objectives

The aim of the master thesis project is to evaluate possible ways to measure the condition on bicycle paths now and in the future. In the project, the focus will be on where it is reasonable to measure along the width of the bicycle path. The objectives of the research will be to collect information about condition measurements for bicycle paths and evaluate measurement methods based on performance and cost-effectiveness. Another challenge is to present the findings so all stakeholders can make use of the content and build a base to continue developing measurement techniques and national and international standards for bicycle paths. The conclusions from this project can contribute to further research towards an objective and standardised method for measuring the bicycle path condition.

1.2.1 Research questions

Is there a difference between measuring the whole width of the bicycle path compared to one specified wheel path line?

Is it beneficial to measure the whole width of bicycle paths?

Where on the bicycle path should routine measurements of evenness be taken?

1.2.2 Delimitations

Measurements for evaluation will be performed with equipment developed by VTI. Other measurement devices for measuring bicycle path condition will briefly be discussed to understand possible development and improvement of the equipment. The measurement will be on separate bicycle paths. Different types of traffic can be found on the bicycle paths for example pedestrians and various kind of bicycles. Environmental benefits of bicycling compared to travelling by other transport modes are not included.

The focus will be on evaluating the measurements regarding the unevenness of the paths' surface layer, not including the construction or the friction on the surface. The master thesis project is limited to investigating where on the width of a bicycle path measurements shall be taken to provide reliable and representative values of the path's condition. The cost and procedure of maintaining the bicycle network based on the measurements will not be included. Only the cost of measuring using the recommended equipment will be considered.

1.2.3 Stakeholders

The result from this thesis can be useful for further research towards a standardised method for measuring the bicycle paths condition with the goal to improve the maintenance planning and the comfort for the bicyclists. VTI will not be responsible for the production of standardised measurement equipment or the measurements, on a larger scale but potentially for the method definition and measurement reliability where they have experience from research on car roads. This knowledge is demanded by the Swedish Transport Administration, municipalities and companies hired to perform maintenance on the road network (Niska Sjögren & Gustafsson, 2011). The Swedish government wants information on how to improve the bicycle network to increase bicycling and improve public health (Regeringskansliet, 2017). The comfort and safety of the bicyclists are highly dependent on the condition of the bicycle path, according to several studies (Niska & Sjögren, 2007). There are many lobbyist groups that are passionate about bicycling and promote actions favourable for increased bicycling and better conditions on the bicycle paths.

1.3 Hypothesis

Because there is a connection between bicycle path condition and bicycle accidents, as stated in the introduction, there is a need for improved maintenance standards for the bicycle path network. To reach an improved standard, objective methods for measuring the condition of the bicycle paths as a base for evaluation are required. The measurement methods used in Sweden today are not sufficient to perform this evaluation in an effective and reliable way.

When bicyclists travel on a bicycle path, they avoid defects on the path by going around them. However, where the bicycle path is narrow and crowded or it is dark outside, the bicyclist might not be able to avoid the defects and then the defect poses a safety risk. So, if the measurement equipment only follows the path of a standard bicyclist, the defects on other parts of the bicycle path will not be detected. It is therefore relevant to measure the whole width of the bicycle path when evaluating the bicycle path condition.

It will be a difference between the measurements, if the whole width is measured compared to one wheel path (Niska & Sjögren, 2007). The difference might not be significant enough to motivate measurements of the whole bicycle network with advanced equipment.

2 Theory

The objective is to measure unevenness in the path surface, but to specify the method, decisions have to be taken regarding how to measure the unevenness and with which equipment. Unevenness measurements can be based on different techniques, for example measurements with profilometers detecting the profile of the surface, measurements with accelerometers detecting the variation in position in one, two or three directions and measurements with profilographs measuring the variation in height of a wheel traveling over the surface (Zang, et.al., 2018). Unevenness measurements with a profilograph are used to calculate the slope variance, which is a part of the Present Serviceability Index, PSI (Pearlman, Nd). There are also more basic techniques of measuring unevenness on the path surface like using a rod and a level to measure height variation or using Straight edge measurement where the distance, from a straight beam with a specific length to the road surface over a certain distance is measured (Zang, et.al., 2018). A range of equipment and measurement vehicles have been developed to measure unevenness (Coenen & Golroo, 2017). Different techniques have varying precision and measures of different wavelengths.

After the measurements are performed the result is evaluated in different ways and recalculated according to standardised classification methods. For car roads, the most common method is to calculate an international roughness index (IRI) value (CEN, 2019). IRI is based on the concept “the Golden car” see Figure 2.1 and calculated from the measured longitudinal profile according to equation 2.1. The calculation is based on a vehicle that is driving in 80km/h. Studies have shown that IRI is not representable for bicyclists’ opinion of the bicycle path condition (Niska & Sjögren, 2014). Bicyclists are sensitive to small defects in the path that would not affect the comfort of a person driving a car (Niska & Sjögren, 2007). Many small irregularities in the bicycle path can be more challenging for the bicyclist’s comfort than a few larger ones because the bicyclist can change their travelling path to avoid obstacles. Therefore, lateral acceleration can be an indication of that the bicyclist has avoided an obstacle or defect on the path (Niska & Sjögren, 2014). The bicyclists comfort on bicycle paths is affected by the type of bicycle and the travelling speed (Niska & Sjögren, 2007). Another method is to measure the vibration in the vehicle caused by riding over a surface because of the correlation between measured vibrations and experienced discomfort.

VTI perform measurements with a standardised vehicle equipped with laser sensors to measure the profile and texture on car roads called the Road Surface Tester, RST (Niska & Sjögren, 2014). According to the report 839 by VTI, where different methods were compared with bicyclists’ experienced comfort on different path stretches, measurements of the mega-texture and the Root Mean Square value, RMS was the most representative methods. RMS calculation can be seen in Equation 2.2.

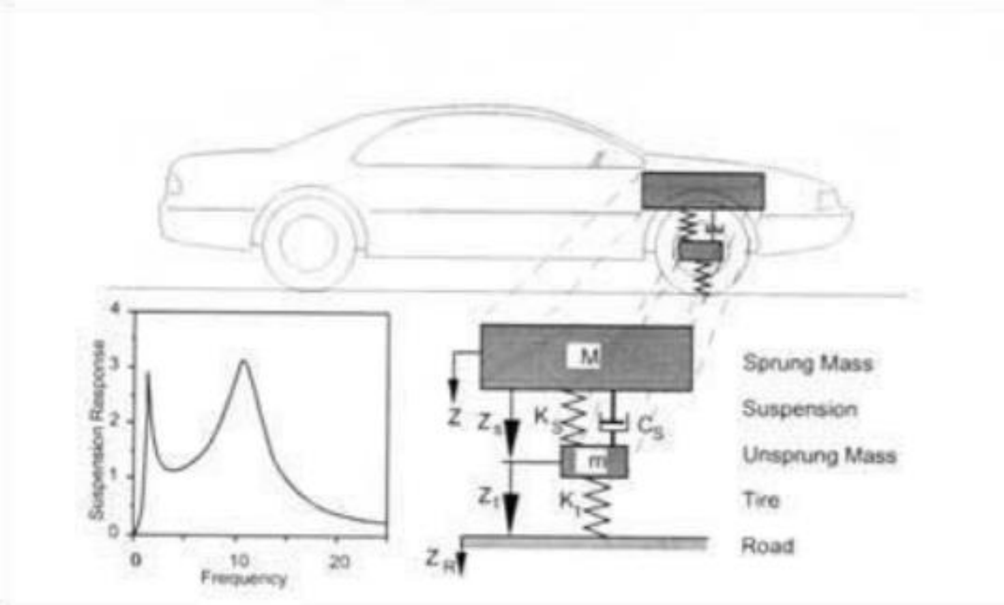


Figure 2.1 Principle of IRI measurements, based on the golden car for measuring roughness on car roads (Sayers and Karamihas, 1998).

$$IRI = \frac{1}{L}\int_0^{L/V} |\dot{z}_s - \dot{z}_u| dt$$

Equation 2.1 IRI (CEN, 2019).

$L = length\ of\ profile$
$V = simulated\ speed$
$Z_s = vertical\ position\ of\ the\ sprung\ mass$
$Z_u = vertical\ position\ of\ the\ unsprung\ mass$

$$RMS = \sqrt{\sum (X_i - \bar{X})^2}$$

Equation 2.2 RMS (Erlandsson, 2013).

2.1 Visual inspection

Visual inspections are very common on roads and bicycle paths, at least as a complement to other more objective measurement methods. In the Pavement Surface Evaluation and Rating, PASER manual developed by the University of Wisconsin-Madison a method is described to evaluate the surface condition of a pavement on a scale from 1 to 10 where a 1 represents bad quality and a 10 represents excellent quality (Walker, 2002). This rating considers surface defects, surface deformation, cracks, patches and potholes detected from visual inspections. The Pavement Condition Index, PCI is another rating system based on visual inspection used to classify the road surface condition (Koglin & Varhelyi, 2018). The road condition can get an index between 0 and 100, 100 is the best possible condition and 0 the worst. The index is calculated based on different deteriorations severity and expansion over the pavement surface e.g. cracking, rutting, bleeding, swelling and ravelling. Koglin & Varhelyi, Corazza et al. have elaborated on adapting the PCI to sidewalks.

The Norwegian Public Road Administration has developed a handbook for inspections of bicycle paths (Niska & Sjögren, 2007). This handbook provides a systematic description of how to evaluate bicycle paths. The evaluation includes a broad range of parameters where one-part regards comfort for the bicyclist related to the bicycle paths condition. Cykelfrämjandet, an organisation promoting bicycling in Sweden has developed an application called" Cykelrapporten" (The bicycle report) where the public can report defects or suggestions of improvement of the bicycle path network (Niska & Sjögren, 2014). In "Cykelrapporten", the problem at a specific location and a suggested solution are described and complemented with pictures, the information collected by Cykelfrämjandet is then sent to the municipalities.

2.2 Measurement equipment for bicycle path condition

The most common methods for evaluation of the bicycle path condition are based on visual inspections (Niska & Sjögren, 2007). With visual inspections, there is a risk of subjective estimations of the path condition. Visual inspections can be performed when driving a car or a bicycle along the path. More objective measurement methods are also in use but with a range of different equipment and measurement methods. Some municipalities are using the same method as for car roads based on the IRI measurements. Heavy equipment used for car roads can damage the bicycle paths because they are constructed for less loading.

Equipment developed to measure the condition of bicycle paths can be mounted on a lighter car-like vehicle, bicycles or be hand driven. To use manual equipment is ineffective because it takes a long time to cover a small part of the bicycle path network (Niska & Sjögren, 2007). Devices mounted on a car or a bicycle can measure the acceleration or the profile and then be recalculate it to a representative value for the bicycle path condition. Accelerometers can be found in most smart phones (Niska & Sjögren, 2014). A smart phone has the possibility to register the position during measurements with GPS and take pictures (Niska & Sjögren, 2007). The accelerometer in a smart phone measure about 1mm of width along the bicycle path. A profilometer can measure up to the whole path width, but advanced laser sensor measurements are more expensive than simple accelerometers (Niska Sjögren & Gustafsson, 2011).

2.2.1 Static and slow moving equipment

The unevenness can be measured with manual equipment. The manual equipment does not provide heavy loads that damage the bicycle paths and can be used where the width is narrow. Some techniques used for manual equipment can be scaled up or mounted on measurement vehicles. The Dipstick equipment plots the profile by measuring the height difference and inclination between two points (Niska & Sjögren, 2007). The Face company manufactures equipment with about 30.48cm between the measuring points (FHWA, 2008). The ARRB TR Walking Profiler was developed in Australia, the equipment can be seen in Figure 2.2. The profile can be read from the variation in inclination of a 23cm long plate pushed along the path surface (Niska & Sjögren, 2007). To measure the surface roughness at a local spot the “Sand Patch-method” can be used (Viman, 2017). The Sand Patch-method is performed by pouring out 25ml of sand with specific particle shape and size in a pile on the pavement surface (CEN, 2019). The sand is then smoothened out in a circle on the surface until it is flat, and the sand is filling the space between grains in the pavement. The sand volume is divided by the area of the circle to get the texture depth, see Figure 2.3.

Figure 2.2 ARRB TR Walking Profiler (Niska & Sjögren, 2007).

Figure 2.3 Sand Patch-method, photo by Andreas Waldemarson (Viman, 2017).

2.2.2 Mobile equipment, accelerometer connected to an app

Accelerometers can be found in most modern smart phones and can be used to measure and evaluate the path surface. Several tests have been performed with this measurement method because if the method is repeatable and reliable it is a cheap way to measure path unevenness (Vittorio, et.al., 2014). The vertical acceleration is calculated from the height deflection of the path profile depending on the speed and time that determines the distance (Yamaguchi, et.al., 2015). An accelerometer can be mounted on different kinds of vehicles, vehicles with low weight are desirable to decrease the risk of damaging the path surface. Accelerometers in smart phones mounted on bicycles have been used by VTI to measure the unevenness on bicycle paths, see Figure 2.4 (Niska & Sjögren, 2014). VTI has also developed an app that registers the path condition based on the accelerometer values.

The method where the acceleration is measured with a smart phone mounted on a bicycle was tested by investigating the correlation between the values from the app and bicyclists' opinions about the bicycle path condition (Niska & Sjögren, 2014). The test was computed by mounting a smart phone on the handlebars of a bicycle and measure a specific stretch on the bicycle path that bicyclist also evaluated. The result was not completely consistent, but conclusions can be drawn about which sections that are in worse condition than other sections. It can also be concluded that the values correlate between the app and the bicyclists' opinions. The repeatability is reliable but singular defects can be missed if it is not crossed by the bicycles' wheel path. A standard for exactly where to measure on the bicycle path is lacking. Both a smooth surface and a very damaged surfaces were evaluated to show correlation between the app and the bicyclists' opinion, but the bicyclists found few larger irregularities more uncomfortable than a regular uneven surface contradictive to the app. E.g. the bicyclists experienced edges between concrete plates with a centre to centre distance of 60cm more uncomfortable than to bike on small gravel.

Acceleration values from 0.7 to 0.8 are considered to be uncomfortable to pass by bicyclists (Niska & Sjögren, 2014). Acceleration values below 0.5 were not noticed by the bicyclists, this value could thereby be a limit that represents an even bicycle path without uncomfortable unevenness. The repeatability is not statistically secured due to the limited test volume. The bicyclists travelled in different wheel paths which can be a part of the cause for different results in their opinion about the road condition. Higher speed leads to higher acceleration values (Alessandroni, et.al., 2017). The result was also dependent on which type of smart phone that was used and parameters like tire pressure, speed and weight (Niska & Sjögren, 2014). The app registers the bicycle's position during the measurements and takes pictures of the path with the phone's camera. The result from the app correlates with measurements by the RST-car for defects with mega texture. Suggested levels of condition are, Red level = an acceleration value over 0.75, Yellow level = an acceleration value from 0.5 to 0.75 and Green level = an acceleration value below 0.5. It is not suitable to let the public collect data with the app because it will result in a large amount of data where the method for collection is questionable and it is hard to know if the result is reliable or not.

The measurements are sensitive to interference in the GPS connection (Niska & Sjögren, 2014). Different smart phones have different placement and quality on their GPS connection (Ranacher, et.al., 2015). The measurements are unique for the specific time and place of measurement, that makes it important to specify where and how the measurements were performed. A stable smart phone holder is important to avoid unnecessary noise. The natural frequency of the smart phone holder will contribute to lager vibrations in that frequency (Yamaguchi, et.al., 2015). "The app needs more development but has a large potential to become a helpful tool to collect information about the bicycle path condition" (Niska & Sjögren, 2014). The information can be used to inform the bicyclists and to get an objective opinion about where maintenance is most needed. It is easy to start measuring with a smart phone and large quantities of data can be collected (Li & Goldberg, 2018). It can be hard to collect exact information with the app but general conclusions about the condition of the bicycle path can be drawn. Measurements with an accelerometer are affected by the bicycles speed, weight and type of tire so it might be desirable to limit the effect of this parameters by going at the same speed with the same bicycle during the measurements.

Figure 2.4 Measurements with an accelerometer in a smart phone mounted on a bicycle (Niska & Sjögren, 2014).

2.2.3 High speed mobile equipment, laser-based surface profilometer

Profilometers measures the profile of the path by detecting the distance to the path surface with a laser sensor. Measurements with laser sensors in an expensive technique (Zang, et.al., 2018). The laser sensor is often combined with equipment measuring acceleration and position to specify the location of the measurement. A profilometer can be made of several laser sensors for wider and precise measurements. Profile measurements should be computed when more accuracy is required (Niska & Sjögren, 2014). The Laser RST used by VTI has 17 laser sensors mounted in the front of a car see Figure 2.5 (Göransson, 2019). The laser RMS can measure over a width of 3.2 meters every tenth centimetre and two additional sensors can be added to increase the measured width. The measured profile can be recalculated to an IRI or RMS value. Measurements with laser sensors is a common technique for measurements on car roads. The laser sensors are often mounted on cars, but they can be mounted on lighter vehicles like manual equipment and bicycles (Gustafschöld & Ossbahr, 2011).

The company Dynatest has developed a method for measuring surface roughness on bicycle paths (Niska Sjögren & Gustafsson, 2011). The measurement equipment is called Lightweight Profilometer (LP) 6450. The equipment includes a sensor measuring distance as well as an accelerometer. Wavelengths between 0.025 and 5 meters can be detected with the equipment every twenty-fifth millimetre. From the measurements, a Bicycle profile index is calculated. The LP method has for example been used in the city of Gothenburg.

Figure 2.5 Measurement with VTI's laser RST (Niska & Sjögren, 2014).

2.3 Measurement methods and procedures

When the measurements are performed, GPS and cameras can be added to the main equipment so the measured information can be related to a specific stretch or point (Niska & Sjögren, 2007). Tested objective measurement methods still need to be supplemented with pictures for correct evaluation (Niska Sjögren & Gustafsson, 2011). Fluctuation in the measurement results can then be identified after the measurement with the help of the pictures. In general, measurements should be performed outside rush hour and measurements on wet or gravelled paths should be avoided.

Measurements with an accelerometer are dependent on the speed of the bicycle. The bicyclist's speed varies with the type of errand the bicycle is used for (Eriksson et.al, 2017). The average speed is between 15 km/h and 30km/h. Bicyclists find it unstable to keep speeds under 10km/h (Ramböll, 2017). The highest speeds can be over 50km/h downhill and on straights (Eriksson et. al, 2017). The average speed is lower uphill, near crossings and where there is a lot of pedestrians or bicycle traffic (Jin, et.al., 2015). Figure 2.6 shows the variation in speed of standard bicycles measured in Copenhagen (Greibe & Skallebæk Buch, 2013). The average speed for bicycles has not changed over the recent years according to an investigation by VTI on bicyclist speed, but it is stated that the speed can be experienced as higher due to a higher volume of bicycle traffic (Eriksson et.al, 2017).

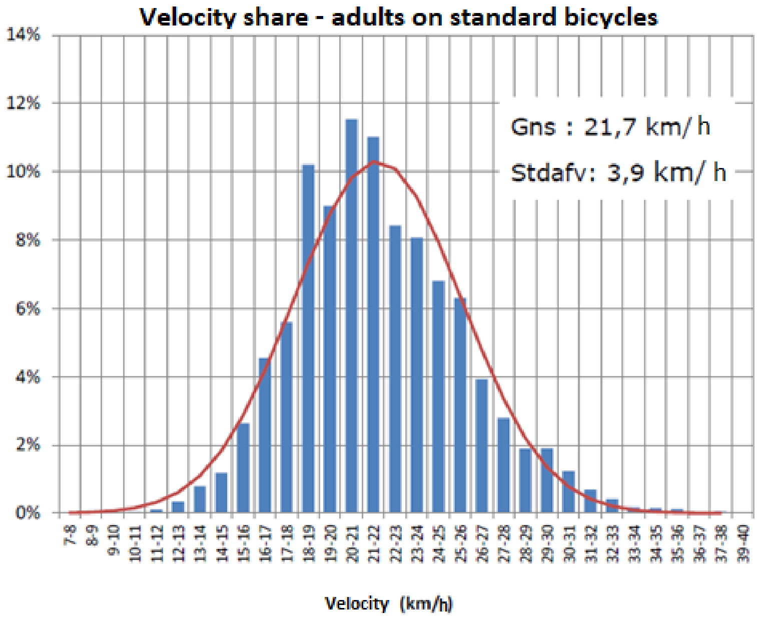


*Figure 2.6 Velocity distribution on bicycle paths, adults on standard bicycles (*adapted from *Greibe & Skallebæk Buch, 2013).*

The individual difference of how bicyclists experience the path condition differs a lot from person to person (Niska Sjögren & Gustafsson, 2011). Therefore, it is important to consider who is bicycling or performing an inspection. When the behaviour of the average bicyclist is studied the test persons should be part of a diverse group. In a study performed by VTI about how the measured unevenness correlated with bicyclists' opinion, representatives from the interest organisation “Cykelfrämjandet” that promotes the usage of bicycles were more critical in their judgement of the bicycle path condition than people in other test groups. The group with members from Cykelfrämjandet might have a lot of experience of travelling on bicycle paths in different conditions. It can be hard for the bicyclists to neglect the surrounding environment when they evaluate the paths surface condition in a visual study. Before testing of bicyclists' opinion about the bicycle path condition, it is preferable to let them run the test rout before evaluation. A test route before the evaluation will make the bicyclists more focused on the task in the second run.

Bicyclists experience discomfort when they encounter deformations with around 10mm of height according to the study by VTI mentioned in the previous section (Niska Sjögren & Gustafsson, 2011). The result from the study were evaluated by classifying the stretch into three path condition classes, where Red = 30% or more measured values over 10mm or an average value over 8mm, considered a not functional acceptable unevenness, Yellow = 10-30% measured values over 10 mm or an average value above 5mm and Green = 10% or less measured values over 10 mm or an average value below 5 mm. Measurements with a 0.5 m long horizontal beam gave the best correlation to bicyclists' opinion in this case, but the horizontal beam only measures unevenness in the wavelength of 20-50 cm and smaller defects in unevenness can also be important for the bicyclists' comfort. It is not only bicyclists that experience discomfort when travelling over a rough surface. For example, the comfort of wheelchair users is highly dependent on that the path surface is smooth (Pearlman, ND). To adapt the measurement method to wheelchair users, PathMET was developed. PathMET is a measurement tool where a laser scanner is mounted on a wheelchair and the vertical acceleration is measured. A sidewalk roughness index in inches/feet can be calculated from the measurements by summation of the vertical acceleration along a certain distance.

The Swedish road association has planned to add all bicycle paths to the National road database, NVDB (Trafikverket, 2010). In this database information about the width and path condition could be added, but this information is not available for all bicycle paths yet, and among the municipalities, different software is used. Implementation and maintenance of bicycle paths are often decided based on experience and local regulations (Koucky & Löwing, 2013). Development of new software are also mostly concentrated on a local level and software adapted to other types of traffic might not be representative for the bicycle network.

2.3.1 Methods used in Sweden

In Sweden, the company Ramböll has done measurements of the bicycle network in several municipalities and contributed to further development towards a comfort index of bicycle paths (Niska & Sjögren, 2007). Ramböll performs "maintenance investigations" with their Road Surface Tester, RST on both car roads and bicycle paths. The investigation includes observations and photo documentation of bicycle paths using GPS-positioning and inventory programs. The path is evaluated every 25 meters regarding, cracking, edge cracking, cracks, potholes, oxidation resulting in stone loss, roots, grass overgrowth and unevenness. The information is used to calculate the expected additional lifetime of the path. In 2011 the municipalities and counties in Sweden published a manual for comfort measurements on bicycle paths developed by Wahlman and Ekdahl at Ramböll (Sveriges Kommuner och Landsting, 2011). By a project financed by the Swedish Transport Administration, SWECO, Ramböll and MOVEA investigated how much space a bicyclist needs on the bicycle path, see Figure 2.7 (Ramböll, 2017). From the investigation, they draw conclusions about how wide bicycle paths need to be. Tables with recommended widths can be found in Appendix A, Table A1-A2.

The manual states that comfort measurement is preferable to decide how the bicyclist experience the unevenness on the path surface (Sveriges Kommuner och Landsting, 2011). Comfort measurements in this manual are performed with a specialised vehicle measuring the unevenness with two laser sensors, see Figure 2.8. The vehicle is small and light, so it is possible to drive on the bicycle paths without damaging the path-surface. The laser sensors detect defects from 0.2-10 meters in wavelength. The vehicle has a speed of 5-15km/h during the measurements. The vehicle is also equipped with a camera and a positioning system. The utmost laser sensor measures about 50 cm from the path edge in both directions, that can be seen in Figure 2.9. Longitudinal cracks and similar defects can be missed by this method; therefore, it is possible for the person operating the measurement vehicle to register additional information about specific defects or parameters that can affect the measurement result. The path stretch will then be classified, based on the measured values, according to a method developed by VTI, presented in Table 2.1, where the maximum value is defined as the maximum distance between a horizontal beam of 0.5 meters and the ground profile over a distance of 0.5 meters.

Table 2.1 Comfort classification (adapted from Sveriges Kommuner och Landsting, 2011).

Comfort class	Description	The share of maximum values over 10mm	The Average value of maximum values
Red	Unacceptable comfort	> 30 %	> 8 mm
Yellow	Lacking comfort	10-30 %	> 5 mm
Green	Acceptable comfort	< 10 %	< 5 mm

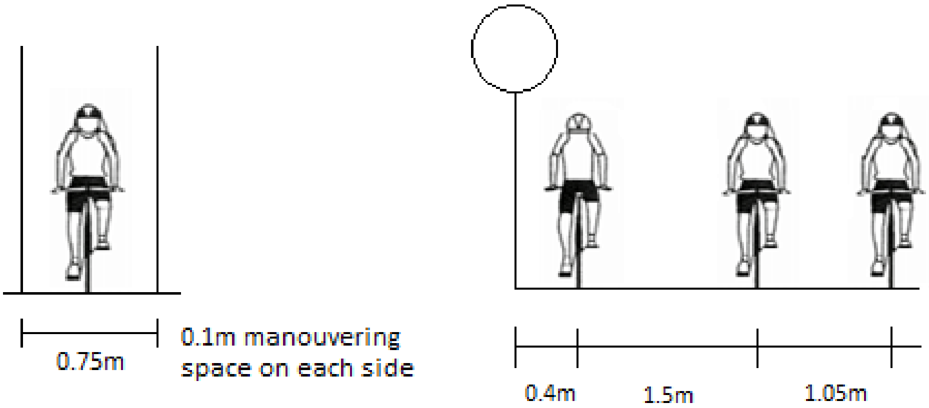


Figure 2.7 Where on the bicycle path bicyclists travels, Swedish Transport Administration (SWECO, Ramböll, MOVEA) (adapted from Ramböll, 2017).

Figure 2.8 Smart car, equipped with two laser sensors (Niska, Sjögren & Gustafsson, 2011).

Figure 2.9 Comfort measurement of Unevenness in two paths (Sveriges Kommuner och Landsting, 2011).

2.3.2 Methods used in Denmark

In Danish bicycle path regulations, the maximum capacity of a 2 meters wide path has a capacity of 2000 bicyclists/h (Greibe & Skallebæk Buch, 2013). Investigations were performed to suggest updates on these regulations. The data collection was measured with video cameras on eight locations around Copenhagen with different prerequisites. 97.8% of the observed bicycles were ordinary bicycles and 1.5% was special bicycles, like bicycles with trolleys etc. the rest were mopeds or other vehicles. Bicycles with trolleys are around 10-20 centimetres wider than a standard bicycle and occupy around 1.3 times more space on the bicycle path. Suggested path width from this study can be found in Appendix A, Table A3. The investigation also considered the location of the bicyclists on the bicycle path which is represented in Figure 2.11 and 2.12.

In Denmark, they perform manual inspections of the bicycle paths as well as unevenness measurements on the path surface (Niska & Sjögren, 2007). Some of the measurements are performed with an accelerometer mounted on a bicycle. The instrument they use is called Shock and Vibration Environment Recorder, SAVER. SAVER was developed in the US. From the measurements a Total Weighted Acceleration value, SVA-value can be calculated, this value is used to assign a comfort value according to Equation 2.3, for the specific stretch. Different comfort values are divided into four different categories, comfort value 1-2 comfortable, 3-4 satisfactory, 5-6 serviceable and 7-10 unsatisfactory. According to a comparison between acceleration measurement with SAVER and evaluation by a test bicyclist performed in Copenhagen, acceleration values under 1G is not considered to feel uncomfortable. The speed for measurements by bike and for recalculating the measured values was 20km/h, as it is the estimated average speed of bicycle travels in Copenhagen.

$Comfort\ value = (0.1 * SVA) + 1$ Equation 2.3 Comfort value (Niska & Sjögren, 2007).

The Danish Road Directorate has also developed measuring equipment that can be mounted on a car instead of a bicycle to be able to perform faster measurements see Figure 2.10, but the result is independent of the speed during the measurement (Niska & Sjögren, 2007). The result from the measurements by car is recalculated and presented with a comfort index as the measurements by bicycle. On the car, two profilometers are mounted to register the profile of the path every fourth centimetre. The profilometers measure 20 and 120 cm from the path's edge. This measurement is assumed to represent the whole width of the bicycle path (Niska Sjögren & Gustafsson, 2011). The profile can be recalculated to vertical acceleration. The value of the vertical acceleration is presented as an average over one-meter length, because with this length it is possible to detect even small deformations and larger deformations do not seem to have an effect on the bicyclists' comfort (Niska & Sjögren, 2007). The car is also equipped with GPS and a camera (Niska Sjögren & Gustafsson, 2011).

In addition to the unevenness measurement, visual inspection is still performed to identify the cause of vertical acceleration variations, to set up a more relevant maintenance plan from the additional information. The car-mounted equipment developed in Copenhagen can register the length of single irregularities divided into different categories observed by the driver (Niska & Sjögren, 2007).

2005 measurements on all bicycle paths in Odense municipality were measured with a laser profilometer and compared to IRI values to develop representative calculations for a Bicycle Profile Index, BPI (Henriksen, 2005). The BPI focus on irregularities in the wavelength of 0.025-5m and are calculated based on the Butterworth Profile Index algorithm. A new BPI is calculated every 50m. The laser profilometer and an accelerometer were mounted in the rear of a smaller car of the model SMART. Values of the profile’s unevenness were measured every 2.5cm and performed about 0.5m from the path edge. Before these measurements were performed the municipality only used visual inspection for evaluation of the bicycle path condition. The tests of the BPI were performed in collaboration with the company Dynatest. In general, the IRI values were lower than the BPI values. IRI was concluded to not cover all the irregularities that a bicyclist can find uncomfortable. The BPI calculated with the Butterworth algorithm of third order were representative to the unevenness on the bicycle path according to this study. The most common BPI values were around 6-9. Other factors than the unevenness can also affect the bicyclist’s comfort, and have to be considered e.g. the traffic volume.

Figure 2.10 Measurement vehicle at the Danish Road Directorate (Niska & Sjögren, 2007).

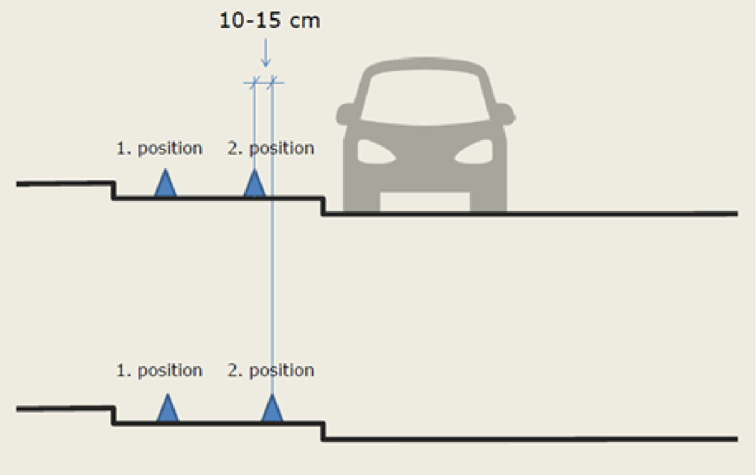


Figure 2.11 Placement on bicycle paths (adapted from Greibe & Skallebæk Buch, 2013).

Figure 2.12 Placement on bicycle paths (adapted from *Greibe & Skallebæk Buch, 2013).*

2.3.3 Methods used in Norway

The Norwegian manual for road construction and maintenance contains instruction of how to construct and maintain the road network. Inspections of the bicycle path are performed to detect defects that need immediate measures (Statens vegvesen, 2004). During inspection experienced bicyclists and stakeholder representatives are invited. The result from the bicycle path inspection is gathered in a database developed by Rambøll Norge AS in collaboration with Statens vegvesen. Before the inspection, information about the bicycle path stretch is collected e.g. traffic data and accident statistics. Inspections of bicycle paths should be done by bike or on foot (Statens vegvesen, 2016). One day is a reasonable length of an inspection of 1-3 km. Maps is an easy way to visualise information about the bicycle path network. If the bicycle path is close to a car road the path is videotaped, the video complements the inspection on site. All the data about the bicycle path stretch is registered on standardised inspection sheets. The stretch is inspected in both directions (Statens vegvesen, 2004). The inspector is equipped with an inspection sheet, GPS, camera, measuring stick, a map and correct clothing for cycling.

The inspection question regarding unevenness is formulated as “Is the quality of the surface good? Look at evenness, holes and cracks, Does the road have good drainage? Look for puddles or mud indicating puddles and Are the drain covers and manhole covers a hindrance/disadvantage to cyclists?” (Statens vegvesen, 2004). The recommended path width is 2.5-3.5 meters. In the manual, it states that the level difference over two meters of length should not exceed 25mm both in length and transverse direction (Statens vegvesen, 2014). Table 2.2 shows the maximum inclination accepted on bicycle paths. Puddles should not cover more than half the path width. Cobblestone height at intersections and refuges should not exceed 20mm. Holes that are a danger for the bicyclists should be rectified immediately, holes in the surface layer should be fixed within a week and cracks over 10 millimetres wide should be sealed. The inspection sheets are compiled after the inspection and presented in an inspection report.

Table 2.2 Maximum inclination on paths for bicyclists and pedestrians (adapted from Statens vegvesen, 2014).

Inclination length (m)	In a central area	Outside the centre area
< 3 m	8%	8%
3-35 m	5%	8%
35-100 m	5%	7%
>100m	5%	5%

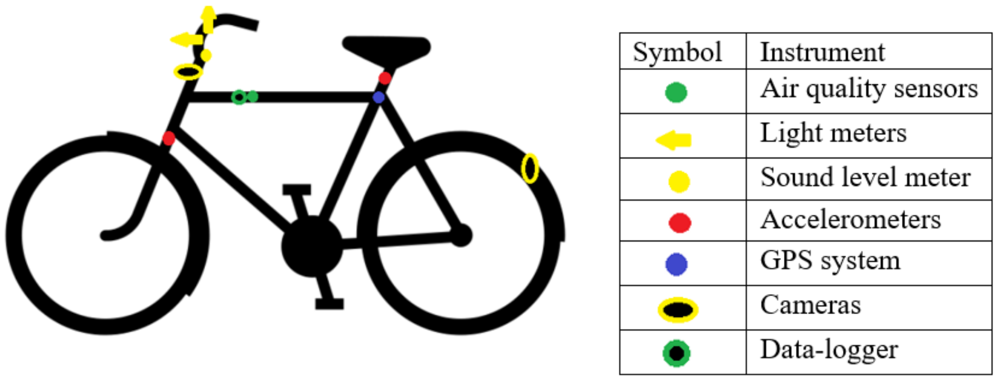
2.3.4 Methods used in the Netherlands and Belgium

The Dutch are famous for their extensive bicycle network. According to the Agency of roads and traffic, the bicycle paths condition should be controlled regularly with objective methods to improve the quality (Agentschap Wegen & Verkeer, 2019). In response measurements, frequencies of 4, 8 and 16 Hz have the largest effect on the human body (Zhang, et al., 2019). The Coefficient of Evenness, EC can be used to analyse the measured response where a higher EC means more uneven surface. The EC is statistically verified to be comparable with bicyclists comfort evaluations.

2.3.5 Methods used in the UK

Cycling England stresses that maintenance should be focused on the width from the edge up to 1.5-2 m starting from the kerb on the bicycle path (Cycling England, 2019). The company W.D.M. Limited has developed a vehicle to measure the road condition of bicycle paths in the UK (W.D.M. Nd). The vehicle is called the Cyclopath. It is equipped with a camera taking pictures every five meters, a GPS that tracks the position with a precision of +-1 meter and laser profilometers with the accuracy of +-1mm. From the measured values on the bicycle path, a Road Condition Indicator score can be calculated every 10 meters but there are no standards regarding the evaluation of a given score.

Taylor and Fairfield at Edinburgh Napier University developed a measurement vehicle called the IntelliBike which were presented at a symposium in Delft 2010 (Niska & Sjögren, 2014). Similarities can be found in other vehicles developed in other countries like Denmark and the Netherlands (Taylor & Fairfield, 2010). The IntelliBike has instruments for detecting position, take photographs, measure vibrations, noise, light and pollution, see the simplified sketch in Figure 2.13. The opportunities to collect different kinds of data are endless.



Symbol	Instrument
🟢	Air quality sensors
⬅	Light meters
🟡	Sound level meter
🔴	Accelerometers
🔵	GPS system
⬭	Cameras
◉	Data-logger

Figure 2.13 IntelliBike, placement of instruments (adapted from Inkwina, 2008).

2.3.6 Methods used in the US

As in many other countries, different stakeholders are responsible for different bicycle path stretches in the US (Simpson et al., 2012). Many different evaluation methods are therefore in use. They gather data about the bicycle network by visual inspection and also sees the public as a valuable source of information that can later be processed by people experienced in path maintenance (AASHTO, 1999). According to the American Association of State Highway and Transportation Officials, AASHTO bicycle paths should provide a smooth surface free from potholes, joints and cracks. The inclination should be maximum, three degrees for longer distances. Bicyclists ride 0.8-1 meters from the curb. See bicyclists operating space in Figure 2.14. Bicycle lanes should not be narrower than 1.2 meters (Transportation research board, 2008). With increased traffic on the bicycle path, the bicycle paths should be wider than in the standard case. Two lane paths should be 4.3 meters wide excluding the space for drainage and parking etc. along the path. The preferred width for one way bicycle paths is 1.5 meters (AASHTO, 1999). For comfort classification Bicycle Level of Service, BLOS a model developed in the US evaluates the bicyclists comfort in mixed traffic depending on the road design, traffic and speed, see Table 2.3 (Niska & Sjögren, 2007). Objective measurements of the paths surface conditions are in most cases not included in BLOS.

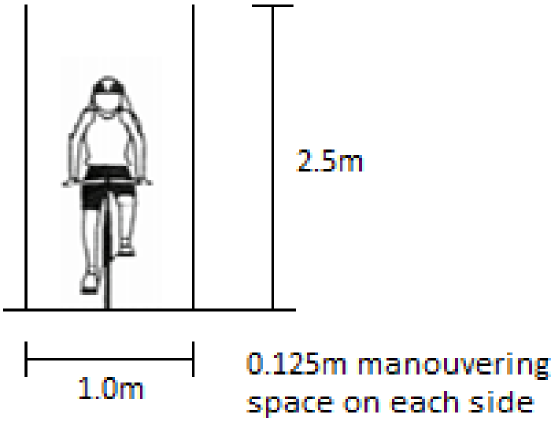


Figure 2.14 Bicyclist Operating Space (adapted from AASHTO, 1999).

Table 2.3 Pavement surface rating, BLOS.

Rate	Surface quality	Pavement Condition
5	Very good	New pavement without cracks and patches.
4	Good	Smoot surface without deterioration.
3	Fair	Noticeably, deteriorated surface condition with rutting, cracks and patching
2	Poor	Limited accessibility due to deterioration of the path surface with extensive cracks and patching
1	Very poor	Extremely deteriorated surface condition with distress >75% of the path surface area

In California pavement surface treatments on bicycle paths were tested by Li, et.al., 2013 at the University of California's pavement research centre. They measured with different measurement methods, in use in the US. For vibration measurements, a bicycle with a three-axis accelerometer and a GPS receiver was used (Li, et.al., 2013). The position was registered every second by the GPS and the accelerometer measured at 200 Hz. According to the preliminary report regarding the measurement of macrotexture by Li, et.al., most bicyclists ride 150 mm from the marked edge of the bicycle path. Vibrations were measured as the average vertical acceleration. Measurements with the speed over 8km/h were included and were then weighted to 26km/h. Different setups in tire pressure and speed were evaluated with the same bicycle. Evaluation of the result showed that the normalisation of speed was representative and that an increase in tire pressure was almost linear to increased vibrations. A lighter bicycle also leads to more vibrations. For unevenness measurements they used an Inertial Profiler (IP) mounted on a normal sized car. Other methods used in the US is presented in Table 2.4. From the measurements, Mean Profile Depth, MPD were calculated. Evaluation by a test group showed that the MPD and vertical acceleration correlates well with the experienced ride quality level. Results from the evaluation by a test group can be found in Table 2.5 and 2.6.

Table 2.4 Measurement methods for pavement surface characteristics (adapted from Li, et.al., 2013).

Method	Equipment	Standard	Index	Operational notes	Sample size notes
Sand patch	Spreader disc and sand	ASTM E965	MTD	Occupies space on the path and takes about 20min/test	Single location measurement
Laser texture scanner	Moving laser	ASTM E1845/ ASTM E2157	MPD/ MTD	Occupies space on the path and takes about 20min/test	Single location measurement
Inertial profiler	High-speed laser	ASTM E1845	MPD/ MTD	Equipment mounted on vehicle operating at highway speeds	Continuous measurements

Table 2.5 Bicyclists subjective evaluation of the macrotexture (adapted from Li, et.al., 2013).

Macrotexture	The share of bicyclists who found it acceptable
2.0 mm	80 %
2.3 mm	60 %
2.5 mm	50 %
2.7 mm	40 %

Table 2.6 Bicyclists subjective evaluation of acceptable inclination (adapted from Li, et.al., 2013).

Inclination on bicycle paths	Acceptable during the maximum distance
5-6 %	240 m
7 %	120 m
8 %	90 m
9 %	60 m
10 %	30 m
>11 %	15 m

2.3.7 Methods used in Australia and New Zeeland

The Australian National Cycling Strategy 2011-2016 states that one priority is to "Improve monitoring and evaluation of cycling programs" (Austroads, 2014). Bicycle paths should have a smoother surface than car roads because a rough surface prevents the bicyclists from travelling at a constant speed that feels comfortable and safe. Bicyclists are estimated to take up a width of 1 m on the bicycle path with 0.1 m manoeuvring space, see Figure 2.15. Unexperienced bicyclists tend to wobble more than experienced bicyclists especially uphill and therefore need more manoeuvring space. The width and length of other types of vehicles, that can be found on the bicycle path is presented in Table 2.7. Bicycle lanes should preferably be at least 2 meters wide. More guidelines on bicycle path width requirements from Austroads can be found in Appendix A, Table A4-A6.

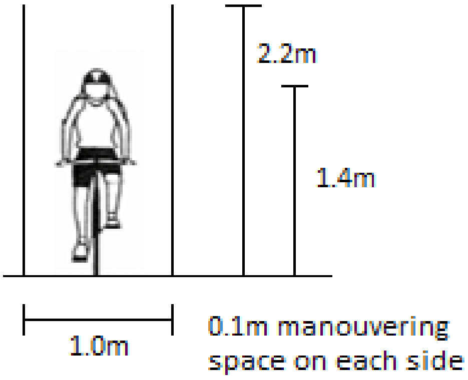


Figure 2.15 Cyclist envelope (adapted from Austroads, 2014).

Table 2.7 Shared path widths (adapted from Austroads, 2009).

Examples of human powered vehicles	Overall vehicle width (m)	Inner turning path radius (m)	Outer turning path radius (m)	Length (m)
Recumbent touring tricycle (Greenspeed)	0.9	1.4	2.3	1.95
Tandem recumbent touring tricycle (Greenspeed)	1.0	3.1	4.1	3.5
Tandem bicycle (Cannondale)	0.56	1.85	2.55	2.45
Bicycle with two-wheel trailer (Coolstop)	0.82	0.7	1.85	2.67
Bicycle with BOB trailer (i.e. baby on board)	0.56	0.9	1.6	2.8
Bicycle with hitch-bike (Thorogood)	0.56	1.7	2.55	1.7

Maintenance inspections should be performed by maintenance supervisors riding a bicycle according to Austroads, 2014 to get the perspective of a bicyclist when performing the inspections. By going by bicycle the bicycle path condition is covered in a more representative way than when going by car on the side of the path (Austroads, 2014). To be able to drive different vehicles for measuring or maintenance the bicycle paths should be designed to withstand a load of a small truck without damaging the path. It is hard to cover every possible defect with an inspection template; therefore, it is important that the maintenance inspectors have a lot of experience with bicycle path inspections. The inspections should be performed at the average speed of bicyclists and with a bicycle representative to the type most bicyclists use. The most common inspection method for path condition is still by visual inspection, following an audit checklist (Austroads, 2009).

3 Method

First, a literature study about measurement methods in use in different countries and research on different measurement methods will be performed. Measurements with an accelerometer measuring in one wheel path and measurements with a laser profilometer measuring the profile in a wider path will be performed in a field study. The measurements will be performed on a bicycle path in Linköping. The data will be used to evaluate the condition of the bicycle path and compare the result between the two measurement methods. Test runs with different equipment will provide a base to decide which method that is preferable to use on the bicycle paths in Sweden (Niska & Sjögren, 2007). Discussion about the possible future development of measurements on the bicycle path network will also be included.

3.1 Data collection

Data for this project will be collected by measurements in the field study and background information mainly collected from reports published by VTI. For the literature study sources of information will be different countries' road administration or equivalent and research from scientific reports. Data from earlier studies with accelerometers on car roads will be provided by VTI for identification of what is important to compare in this project. The files will be sent in XPS format, containing coordinates in SWEREF99TM and associated vertical acceleration values.

3.2 Literature study

The literature study will focus on where along the bicycle path width other countries measure their existing bicycle paths, which measurement method they use and their reflections on what to use in the future.

3.3 Measurement

The measurement will be performed during spring 2019 on dry bicycle paths when sand and gravel from the winter operation has been removed. Rocking in curves etc, not depending on the road surface will be filtered from the measurement data. The measurement equipment is mounted on a bicycle trolley drawn by an electric bicycle with specifications presented in appendix B. The trolley is chosen to be stable and is a standard bicycle trolley on the market so the method can be implemented on almost any bicycle trolley.

The speed during the measurements will not be constant, but to facilitate the comparison the speed will be around 10 km/h. A lower speed than the average bicyclist travelling speed is chosen to avoid lost data points during the measurements. The measurements will be performed in three different wheel paths, see Figure 3.1. The accelerometer in the smart phone and the laser profilometer will measure the same stretch at the same time. To investigate the repeatability Path 2 in Figure 3.1 is measured three times.

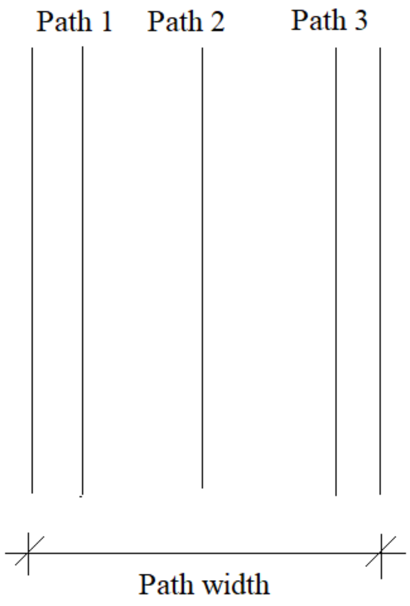


Figure 3.1 Repetition of measurements in different paths.

3.3.1 Equipment

The measurement equipment is developed by VTI. The measurement equipment consists of two main parts, a line profile sensor using laser and an accelerometer included in a smart phone. The laser profilometer is mounted on the handlebar of a bicycle trolley, see Figure 3.2. The laser profilometer is of the type Gocator 2375, for more specifications see Appendix B. The laser sensor measures the profile every fifth millimetre in the longitudinal direction. In the horizontal direction, every 2.5 mm is registered and with the mounting height of around 1.00 m from the ground, it can detect the horizontal profile within a width of over 50 cm. A car battery is placed in the bicycle trolley to supply the measuring equipment with electricity and act as a load avoiding vibrations in the trolley when measuring.

The smart phone is mounted in a box, placed on a front mounted luggage carrier on an electric bicycle which is also carrying the bicycle trolley, see Figure 3.3 and 3.4. The smart phone has an installed application developed by VTI which is measuring the acceleration along three axes, lateral, vertical and horizontal acceleration. The position of the measurement will be detected by the GPS in the smart phone. The smart phone will take pictures of the path every 10th meter through the hole in the box in Figure 3.3. Data from the app can be unreliable in curves where the bicycle is inclined at high speeds. The bike trolley will in the future also be equipped with light sensors to be able to detect direct and reflecting light on the bicycle path.

Figure 3.2 Bicycle and trolley with mounted equipment, left side (Leif Sjögren, 2019-04-01).

Figure 3.3 Bicycle and trolley with mounted equipment, front view (Leif Sjögren, 2019-04-01).

Figure 3.4 Box for mounting of smart phone (Leif Sjögren, 2019-04-01).

3.3.2 Test section

A visual inspection will first be performed to locate suitable stretches with varying path conditions for the measurements. The distance will be around 200 meters in the first measurement to be able to process the data.

3.3.3 Evaluation

A model is chosen to recalculate the values measured by the laser profilometer to make them comparable to accelerometer values representing a specific quality of the bicycle path condition. From the application, the crest factor is used to calculate a representative value of the vertical acceleration over a 5 m section on the stretch. The crest factor is calculated by taking the highest accelerometer value measured on the 5 m section and divide it by the average accelerometer value. The laser sensor measurements will be recalculated so it represents the height variations over the width. For every point along the width, the crest factor will be calculated over a 5m section, with the same method as for the application values. The maximum crest factor in the section will be compared with the values based on accelerometer measurements.

The format for presenting the accelerometer result has been changed from previous reports (Niska & Sjögren, 2014). So, the previous classification cannot be used to classify the bicycle path condition. By plotting the result in an XY-diagram correlation between the different measurement methods will be evaluated. Abnormalities caused by external factors will be identified by comparing pictures of the stretch with the measured values. The difference in the measurements with different methods will serve as a base to conclude if it is necessary to measure in more than one wheel path to achieve a representative classification of the bicycle path condition.

4 Measurements in Linköping

The measurements were performed 16/4-2019. The weather was sunny, some shadows from trees near the bicycle path were covering the wheel path. The speed during the measurements was around 10 km/h ± 1km/h.

4.1 Test section

The measurements were performed near VTI's office on the bicycle path parallel with Universitetsvägen, see Figure 4.1. The width of the bicycle path is approximately 3,3 meters. The starting point was located at the south end of the bus stop Mäster Mattias väg, see the red star marked with 1 in Figure 4.1. The stretch passes a crossing where the pavement is damaged by the heavy traffic and there are both longitudinal and horizontal cracks along the stretch. The stretch ends around 180 m from the starting point where a well that provides an uncomfortable obstacle for the bicyclists is passed. Results from a visual inspection of the stretch can be seen in Appendix C.

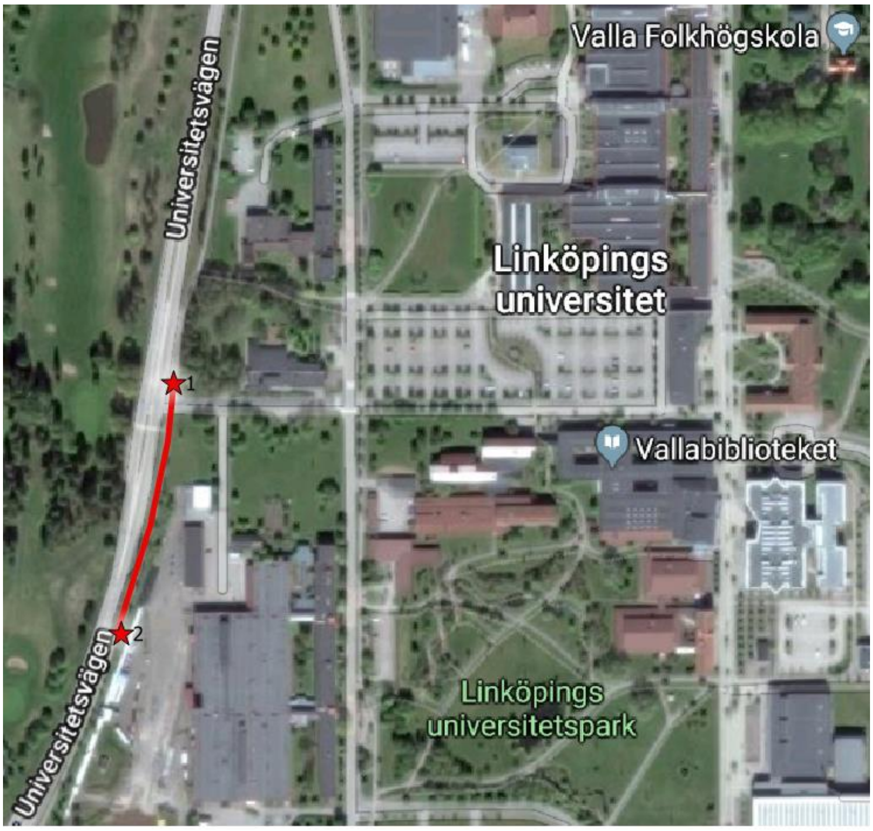


Figure 4.1 Location of measured stretch in Linköping (OpenStreetMaps contributors).

4.2 Data from the VTI-application

There is a difference in measurements in different wheel paths on the same bicycle path, as can be seen in Figure 4.2. There is a peak in Path 3 at 90 meters which is larger than in the other paths. At 72 meters into the stretch, there is a horizontal crack on the bicycle path, which all measurements indicate. The result from the application values shows that the first part of the stretch is less smooth than the last 70 meters. Measurements in the same wheel path, Path 2 also shows a difference between the different measurement runs (see Figure 4.3). Some correlation can be seen between Run 1 and Run 3.

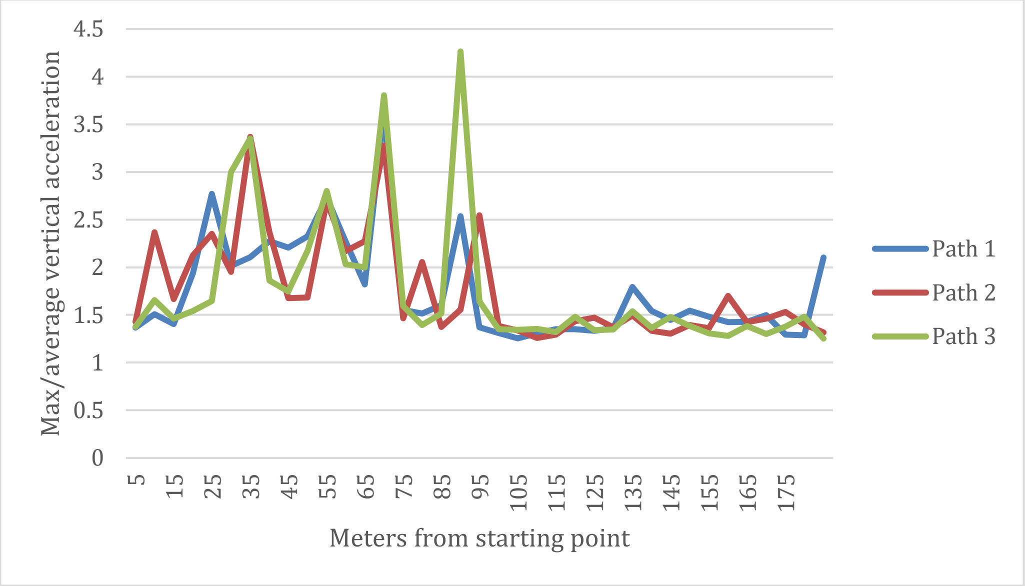


Figure 4.2 Measurements Path 1, Path 2 and Path 3

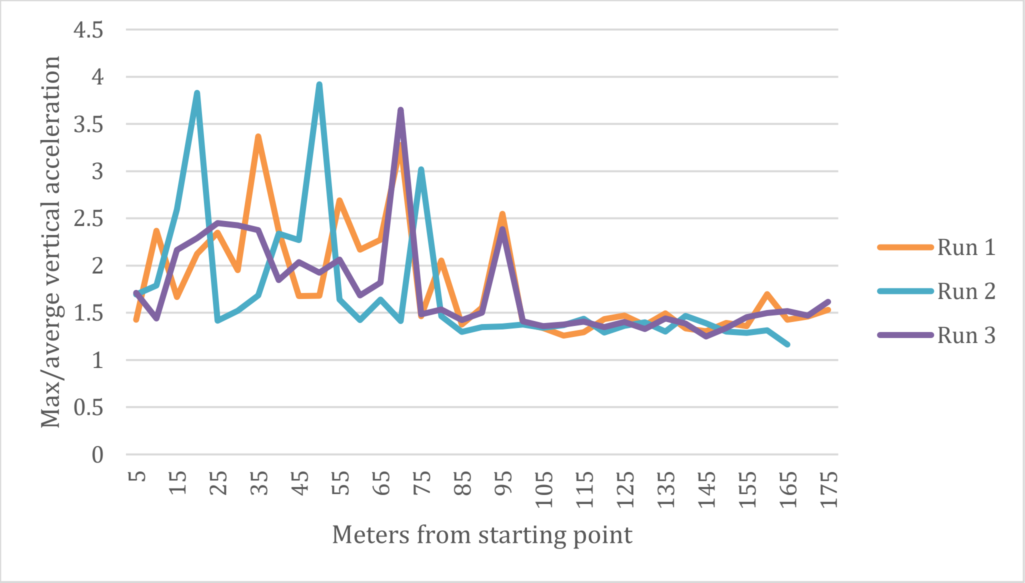


Figure 4.3 Measurements Path 2, three different runs

4.3 Data from the laser sensor

In Figure 4.4 the result from measurements with the laser sensor can be seen. The peaks in the measurement do not correlate with each other nor with the visual observation of the bicycle paths surface condition. The only significant correlation can be seen in Figure 4.5 where all runs show a peak at 40 meters. In Appendix D all measurements are plotted separately.

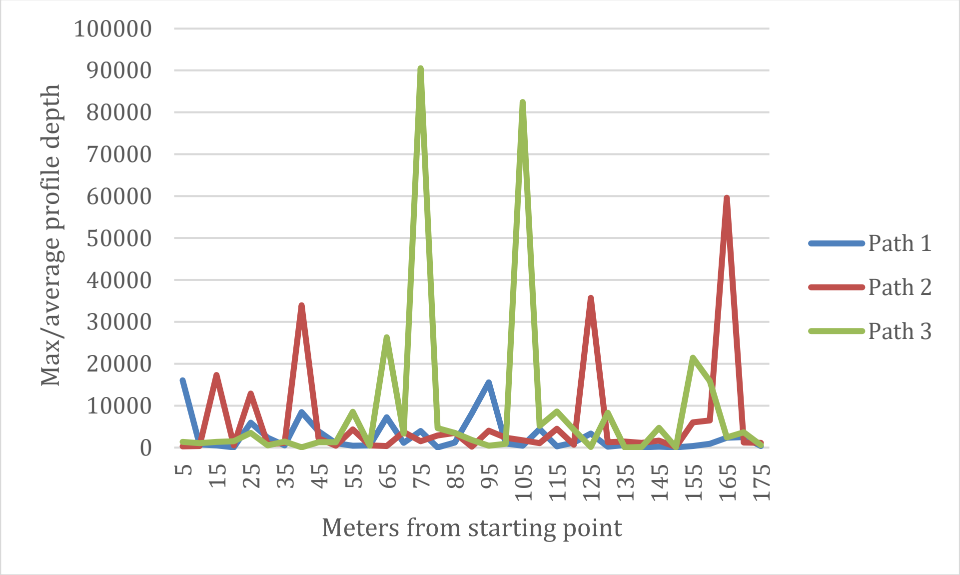


Figure 4.4 Measurements Path 1, Path 2 and Path 3

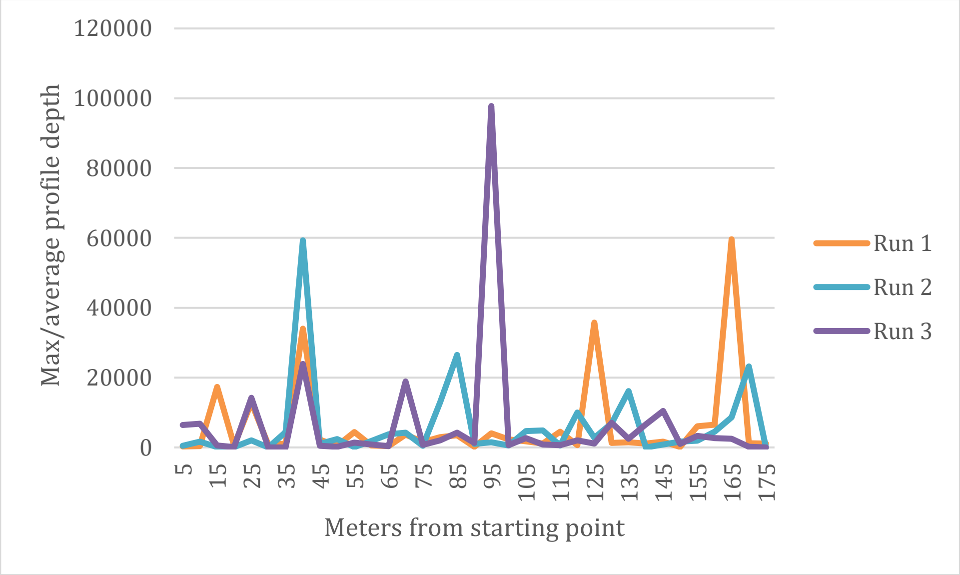


Figure 4.5 Measurements Path 2, three different runs

4.4 Data compilation

When comparing the result from both accelerometer and profilometer measurements no functional relationship can be found for any of the paths, see Figure 4.6 – Figure 4.8. The recalculated values from the profilometer are plotted on the Y-axis and values from the accelerometer on the X-axis.

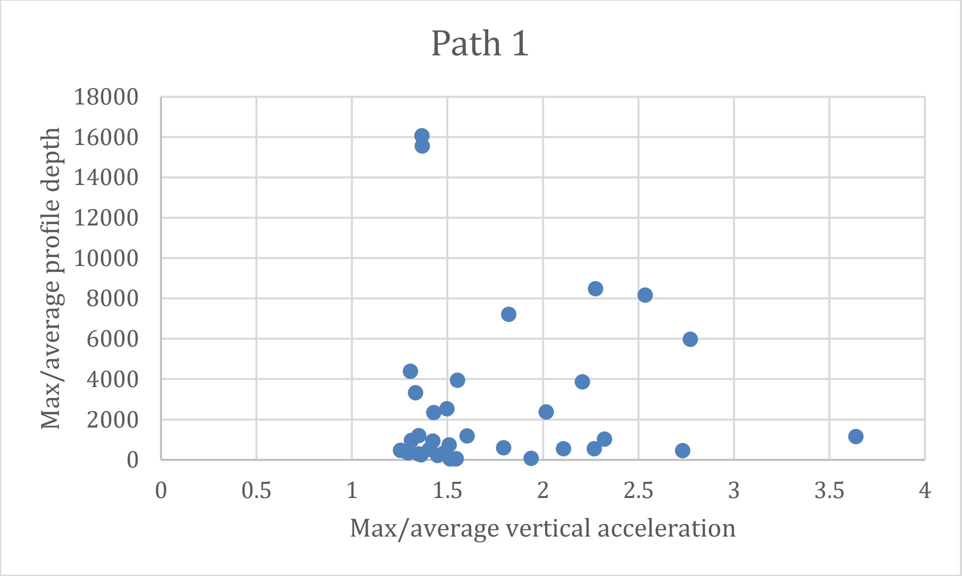


Figure 4.6 Measurements Path 1 with different measurement methods

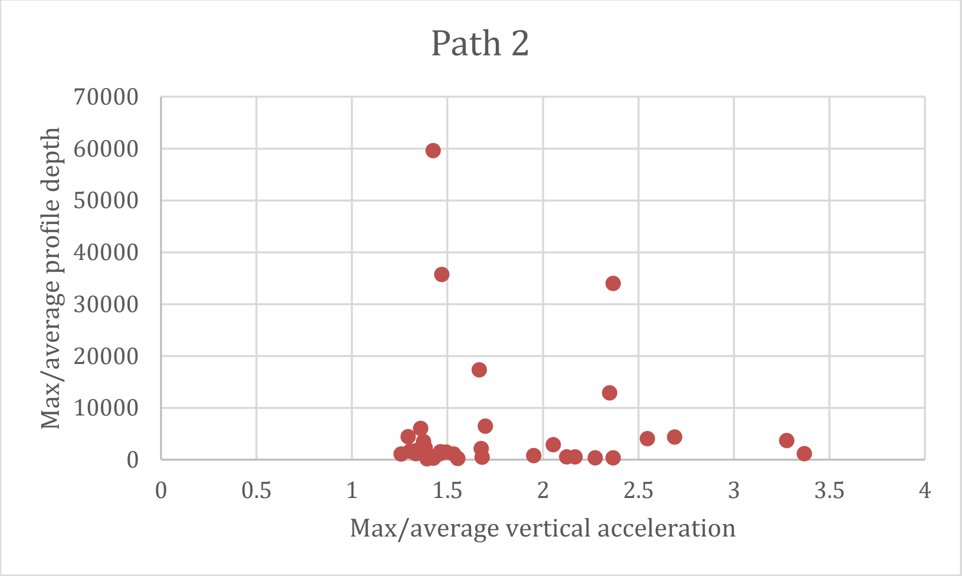


Figure 4.7 Measurements Path 2 with different measurement methods

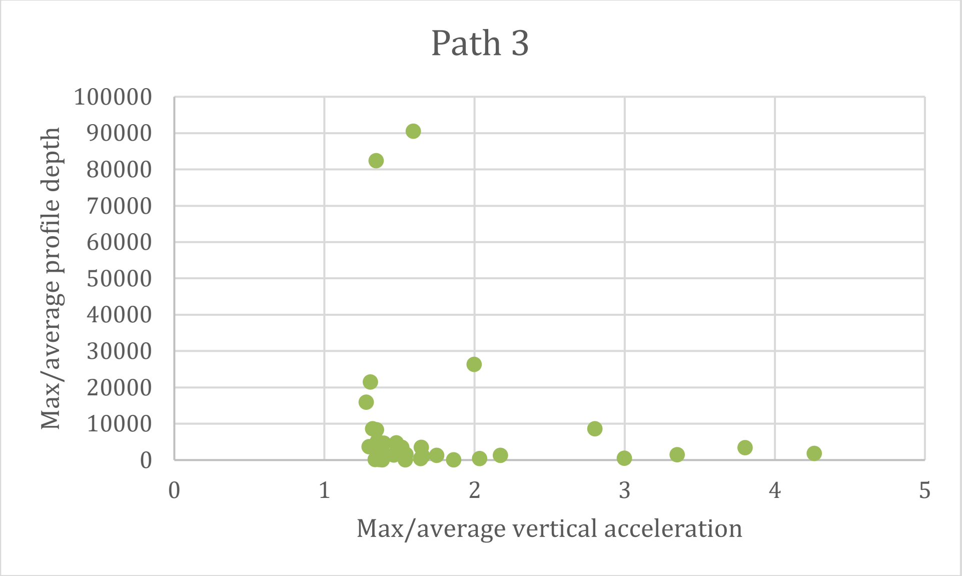


Figure 4.8 Measurements Path 3 with different measurement methods

5 Discussion

Wider bicycles or other vehicles might not have the chance to avoid deformations in the path. In situations where the bicyclists need to avoid an obstacle or pass a pedestrian, or another bicycle will make them leave the standard wheel path. Bicyclists not noticing defects during the night due to darkness and the situations stated above speaks for measurements of the whole bicycle path width. The different measurement methods have different precision, and a more important question might be if this precision is needed or not. On a new path where the road condition is very similar over the width during a long stretch on the path a precise method is redundant.

5.1 Comparison between accelerometer and profilometer values

The application provides values with a small variation depending on where on the bicycle path the bicycle travels. This can be seen as a sign of that it does not matter where on the bicycle path the measurements are performed to get a representative result for the whole path width or that the method is not detailed enough. Even if the variation is small it still defers between different wheel paths and depending on if the bicycle passes the roughest part of the bicycle path or not the classification might differ. All measurements seem to indicate that there is a horizontal crack at 72m into the stretch, but other known defects in the path surface cannot be located by studying the result.

Like previous studies have shown regarding the validity and repeatability of measurements with an accelerometer in a smart phone mounted on the bicycle, the accelerometer values show an indication of the path surface condition. All measurements indicated that the first part of the stretch has a higher unevenness than the last part. This is also in line with the visual inspection where the crossing with a rougher surface was at the beginning of the stretch and at the end part, the path surface was smoother. Run 2 of the measurements in the second wheel path is not correlating with the other runs, the result from that measurement is questionable and the difference can be due to varying speeds in the different runs or errors in the calibration of the measurement equipment.

Variations between Path 1, 2 and 3 imply that the laser sensor detects more information about the bicycle path's unevenness than the accelerometer. When comparing the result from the measurements with the laser sensor, with visual inspections no correlation can be found, neither when comparing it to the accelerometer values. The result indicates that the profilometer measurements performed with this method are not good enough to detect significant deteriorations in the bicycle path surface.

5.2 Recommendation

More research needs to be computed on how to develop profilometer measurements for bicycle paths, both regarding the validity, reliability and repeatability of the measurements and how the measurements correlate with bicyclists experience of the path surface. Neither of the tested measurement methods in this study resulted in conclusions about the surface unevenness in significance with a visual inspection. Because of the downsides with visual inspections, that it is not repeatable, and the reliability depends on the person performing the inspection it is important to continue the development of a more impartial measurement method.

5.3 Sources of error

The accelerometer measurement covers the wheel path that the bicycle passes, this makes the choice of wheel path important for the measurement result. The speed was lower than the speed of a standard bicyclist during the measurements in order to avoid loss of data. Speed variations affect the measured result. When meeting other bicyclists or pedestrians, the path of the bicycle changes slightly even if this was avoided, to as large extent as possible. When the measurement was repeated three times the path was not exactly the same, because of this the result might be similar to measurements in three different wheel paths close to each other instead of showing the exact same result.

The damping of the bicycle trolley was dismounted but vibrations in the trolley can affect the measurements significantly and too few measurement runs were performed to verify the reliability of the profilometer. Other sources of error can be leaves and gravel on the bicycle path or errors in the calibration of the measurement instrument. Human errors in the measurement method are probably the largest source of error but another evaluation method might result in more representative values.

5.4 Alternative methods

The study could have a larger focus on verifying measurements with the laser profilometer on bicycle paths. Another measurement method and other equipment could have been used. Adaption of the resolution time and measurement intensity would make it possible to measure at a higher speed without any data loss. The measurements should have been performed in the exact same wheel path, for example by drawing the wheel path on the bicycle path surface, to follow during the measurements.

In addition to the measurements in this study, the trolley could have been equipped with additional measurement devices, for example, measuring the inclination and radius of curves. Another relevant method would be to test the Danish way of measuring bicycle path condition and adapt it to Swedish conditions.

5.5 Suggested further studies

To continue the research towards a standardized method on how to measure unevenness on bicycle paths, ideas regarding further studies in the topic have emerged during the study. As mentioned in the previous section other methods, for example, the method used in Denmark can be investigated on Swedish bicycle paths. Studies can be done both to develop the bicycle trolley further and test new methods on how to classify the data based on bicyclists experienced safety and comfort. With more reliable equipment and methods the volume of the measurements can be extended, this requires an effective way to process the data and identify outliers.

Regardless of which measurement method that is chosen between the two investigated methods in this study, an interesting input would be to investigate were on the bicycle path bicyclists positioning their bicycle. This would indicate, were the most representative wheel path on the bicycle path is located. The information on where on the bicycle path the bicyclists travel can be gathered in field studies, where the wheel path of different bicyclists is observed. The position of bicyclists can be detected by sensors, on the bicycle or on the bicycle path. Camera and radar detection have been used to count the number of bicyclists on bicycle paths (Ryus, et.al., 2016). The detection for this purpose has to be very precise, over the capacity of standard GPS equipment.

Measurements of the effective width on bicycle paths have many applications. The effective width means the width on the bicycle path where it is possible to walk or drive a vehicle. The width can be limited by obstacles placed on the path, bushes intruding the space on the path or loss of asphalt at the path edges. The effective width can be hard to measure due to the large variation in the character of bicycle paths and the lack of data about old bicycle paths. To detect potential problems with the bicycle paths' surface roughness in the future, investigations of the surroundings and underlying ground conditions can be performed (Niska, 2006). The investigations can be done with a Ground Penetration Radar, GPR which detects defects and roots growing below the path that can potentially be a problem in the future.

6 Conclusion

To reach the aim of developing a standard for measuring unevenness on bicycle paths the whole width of the bicycle path has to be measured in a more reliable way than measurements with a profilometer mounted on a bicycle trolley, can provide today.

Is there a difference between measuring the whole width of the bicycle path compared to one specified wheel path line?

There is a difference in measuring the whole width of the bicycle path compared to one wheel path. This can be seen when comparing, the measurements with the profilometer covering 520mm of the bicycle path width and the accelerometer covering one wheel path. No correlation can be seen between the two methods. A difference can also be seen between measurements with the same measurement method in different wheel paths.

Is it beneficial to measure the whole width of bicycle paths?

In this study, there was no clear evidence that a full-width measurement will provide more useful information than a measurement in one wheel path. This is due to the limitations in the measurement methods. Measurement with an accelerometer in one wheel path is missing changes in unevenness outside that wheel path. If the goal is to get an exact representation of the unevenness over the bicycle path width, then the accelerometer values are not enough. The laser sensor is more sensitive to changes in unevenness over the bicycle path width, but when the laser sensor is mounted on a bicycle trolley the sources of error seem to have a significant impact on the measured values. The reliability and repeatability of measurements with a profilometer have been studied further and compared with bicyclist evaluations, this would be useful for comparation to the accelerometer measurements as well.

Where on the bicycle path should routine measurements of evenness be taken?

This question depends on the purpose of the measurement result. A rough indication of the bicycle path condition can be done with an accelerometer in a smart phone, but if all accidents, which have irregularities as the main cause should be avoided, all irregularities on the bicycle path have to be detected.

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Appendix

A: Recommended path widths

B: Equipment specifications

C: Visual inspection

D: Measured values

Appendix A

The total width of a bicycle path affects the accessibility for the bicyclists. In Appendix A, recommended path widths are presented. The width also effects where on the bicycle path bicyclists are most likely to travel, which can be important when measurements are performed, especially when the measured width is limited. Table A2 shows recommended pathwidths from a study in Sweden based on observations presented in Table A1. The recommended widths wary from 1.0-5.1 m depending on the number of lanes and barriers along the bicycle path. Table A3 shows recommended bicycle path widths according to Greibe & Skallebæk Buch, 2013. The widths in Table A3 are the recommended minimum widths which are slightly narrower than the widths in table A2. Table A4-A6 shows the recommendations according to Austroads on bicycle path widths. Most two-way bicycle paths are recommended to have a width of 2-3 m.

Table A1 Summarized values of where the bicyclists travel on the bicycle path from a study computed by SWECO, Ramböll and MOVEA at the request of the Swedish Transport Administration (adapted from Ramböll, 2017).

	Measurement between	Recommended distance	Distance according to VGU
Distance to path edge with a side barrier	Bicycle wheel and path edge	0.75 m	
Distance to path edge with a side barrier	Bicyclists and path edge	0.4 m	> 0.2 m
Distance to path edge without side barrier	Bicycle wheel and path edge	0.35 m	
Distance to path edge without side barrier	Bicyclists and path edge	0.1 m	> 0.2 m
Distance between bicyclists when overtaking	Bicycle wheels when overtaking	1.05 m	
Distance between bicyclists when overtaking	Bicyclists when overtaking	0.3 m	
Distance between bicyclists when passing	Bicycle wheels when passing	1.5 m	
Distance between bicyclists when passing	Bicyclists when passing	0.75 m	Space class: A = 0.75 m B = 0.3 m

Table A2 Conclusion on bicycle path widths in Sweden (adapted from Ramböll, 2017).

Bicycle path	Standard	The flow of bicycles (bike/h/lane)	Possibility for overtaking	Recommended path width (m), with side barrier on both sides	Recommended path width (m), with side barrier on one side	Recommended path width (m), without side barrier
One-way	Low	< 360	No	1.5 m	1.25 m	1.0 m
One-way	Average-high	360-1440	Yes	2.5 m	2.25 m	2.0 m
Two-way	Low to average	< 360 in one direction	Yes, but limited	3.0 m	2.7 m	2.4 m
Two-way	Average-high	< 1440 in one direction and < 360 in the other	Yes, but limited	4.0 m	3.7 m	3.3 m
Two-way	High	< 1440 in both directions	Yes, in both directions	5.1 m	4.8 m	4.5 m

Table A3 Suggested width of bicycle paths in Denmark (adapted from Greibe & Skallebæk Buch, 2013).

Recommended path width including 0.15m kerbstones	With parked cars along the road	Without parked cars along the road
minimum path width for two-lane paths with low service level	1.80m	1.90m
minimum path width for two-lane paths	1.95m	2.05m
minimum path width for two-lane paths with high service level	2.25m	3.25m
minimum path width for three-lane paths	3.05m	3.15m

Table A4 Bicycle path widths, in Australia (adapted from Austroads, 2014).

Path width	Local access path	Commuter path	Recreational path
Desirable minimum width	2.5 m	3.0 m	3.5 m
Typical min-max width	2.5-3.0 m	2.5-4.0 m	3.0-4.0 m

Table A5 Separate one-way path widths, in Australia (adapted from Austroads, 2014).

Path width	Bicycle path	Footpath	Total
Desirable minimum width	1.5 m	1.5 m	3.0 m
Typical min-max width	1.2-2,0 m	>1.2 m	>3.4 m

Table A6 Shared path widths, in Australia (adapted from Austroads, 2009).

Path width	Bicycle path	Footpath	Total
Desirable minimum width	1.5 m, one-way 2.5 m, two-way	1.5 m, one-way 2.0 m, two-way	3.0 m, one-way 4.5 m, two-way
Typical min-max width	1.2-2.0 m, one-way 2.0-3.0 m, two-way	> 1.2 m, one-way > 1.5 m, two-way	> 3.4 m, one-way > 4.5 m, two-way

Appendix B

The bicycle

The bicycle is of the brand Walleräng, model M01, see Figure B1. During the measurements, the bicycle computer was set on [A] HIGH. On the luggage carrier in the front, a box is mounted where the smart phone is placed during the measurements.

Figure B1 Bicycle used for measurements (Leif Sjögren, 2019-04-01).

The trolley

The trolley is of the brand Thule, see Figure B2. The damping of the trolley is disabled. A distance meter mounted on the right wheel is detecting the distance from the starting point. The laser sensor is mounted on the handlebar. The trolley is carrying a battery and electronic components to transfer the profilometer data from the laser sensor to a computer also placed in the trolley beside the battery during the measurements.

Figure B2 Trolley used for measurements (Leif Sjögren, 2019-04-01).

The application

The application is developed by Sverker Nilsson with support from Leif Sjögren and Thomas Lundberg, at VTI (Niska & Sjögren, 2014). The application program is written in Java from open source code. It is compatible with Android software. The application collects acceleration data in three directions at specific points registered by the smart phones' GPS. The calculation program Readsensor, written in C++ is used to process the data. In Figure B3 the repeatability of the acceleration measurements with the application is visualised. The data does not provide an exact acceleration value at a specific point, but repeated measurements can indicate the location of deteriorations on the bicycle path.

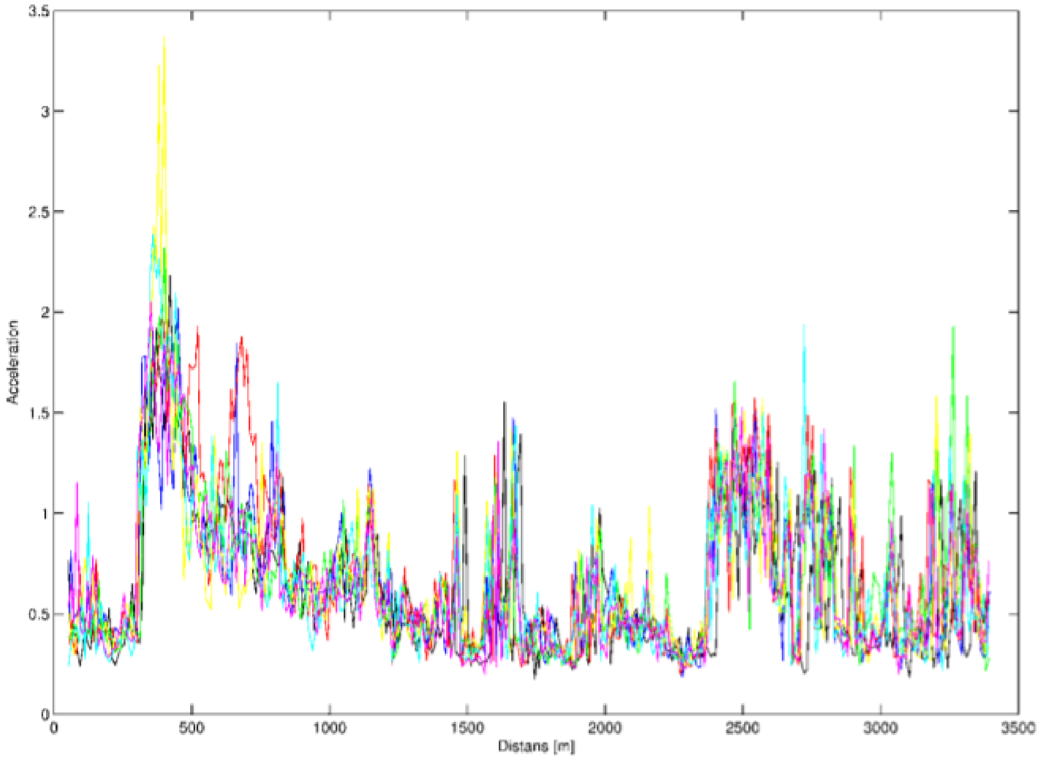

Figure B3 Data collected by the app, with the same bicyclist and travelled distance along the same route (Niska & Sjögren, 2014).

The profilometer sensor

The profilometer is a Gocator laser sensor with the product number 2375A-3B-N-11, produced in Canada by LMI Technologies. The emitted wavelength is 808 nm and the peak power is 450 mW (LMI Technologies, 2014). The sensor is mounted under a mounting plate with the laser emitter directed towards the ground. The mounting plate has spirit-levels in front to rear and left to right direction mounted horizontally on top of the mounting plate. The sensors components can be seen in Figure B4.

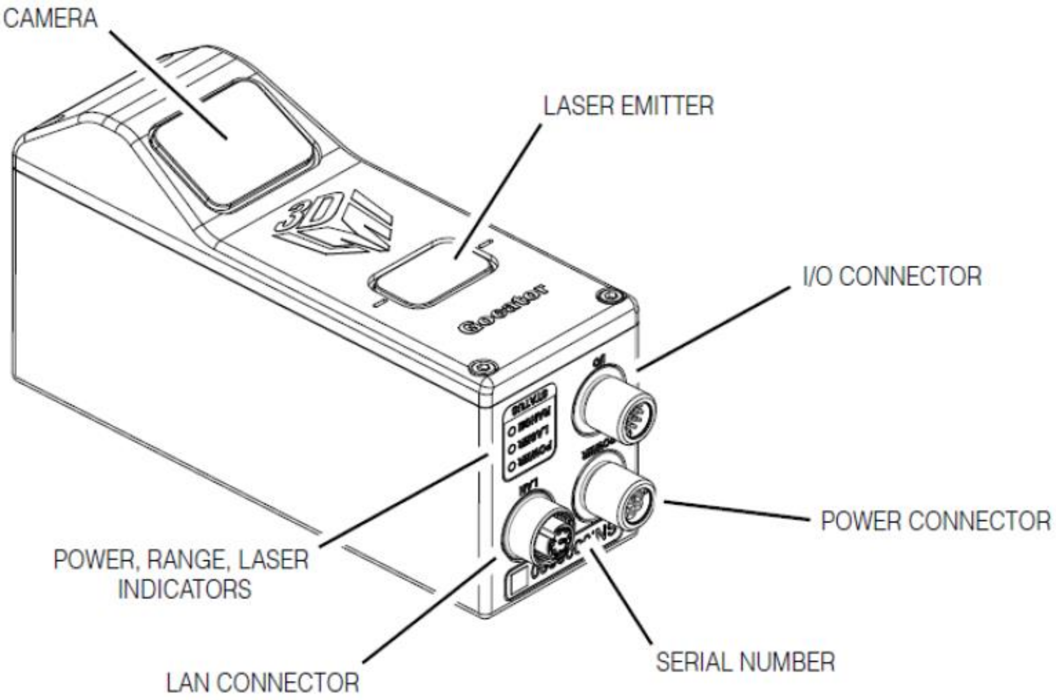

Figure B4. Gocator 2300 Sensor (adapted from LMI Technologies, Nd).

Appendix C

Meters from starting point	Path 1	Path 2	Path 3
0			
19	Road junction		
20	Road junction		
21	Road junction		
22	Road junction		
23	Road junction		
24	Road junction		
25	Road junction		
26	Road junction		
27	Road junction		
28	Road junction		
29	Road junction		
30	Road junction		
31	Road junction		
32	Road junction		
33	Road junction		
35		Cracks	
36		Cracks	
37	Cracks	Cracks	Cracks
44	Well		Loss of surface material
48	Cracks		
53			Patching
54			Patching
55		Pothole	Patching
56		Pothole	Patching
57		Pothole	Patching
59		Loss of surface material	
61	Cracks		
64		Pothole	
67	Pothole		
70			Cracks
72			Patching
73	Horizontal crack		
93	Pothole	Pothole	
140	Cracks		
146	Cracks		
147	Cracks		
148	Cracks		
149	Cracks		
150	Cracks		

151	Cracks		
152	Cracks		
155	Cracks		
156	Cracks		
157	Cracks		
158	Cracks		
159	Cracks		
160	Cracks		
161	Cracks		
170	Well		
172			Cracks
173			Cracks
174			Cracks
175			Cracks
176			Cracks
177			Cracks
178			Cracks
179			Cracks
180			

Appendix D

Data collection on the stretch in Linköping, measured with an app in a smart phone placed on the front mounted luggage carrier. The tables C1, C2 and C3 contain the maximum, average and weighted maximum/average value in mm for every fifth meters along the stretch. Path 1 is the wheel path on the left side of the bicycle path, Path 2 is in the middle and Path 3 is on the right side. Only the first run in all paths are represented.

Table C1 Path 1

Maximum	Average	Maximum/Average
13.424699	9.824061	1.366512188
14.748733	9.774874	1.508841276
13.855668	9.864497	1.404599586
19.307432	9.964015	1.937716135
27.005026	9.743106	2.771706086
19.937126	9.885965	2.016710063
20.743998	9.844804	2.107101171
22.242813	9.77627	2.275184004
21.656216	9.814425	2.206570063
22.848564	9.838321	2.322404851
26.882917	9.839765	2.732069016
22.431961	9.884294	2.26945516
17.82777	9.793756	1.820320079
35.68906	9.806628	3.639279302
15.337725	9.88098	1.552247406
14.904361	9.844033	1.514050364
15.773482	9.838843	1.603184619
24.969893	9.84591	2.536067642
13.458219	9.829383	1.369182505
12.883593	9.827102	1.311026703
12.337698	9.835884	1.254355777
12.823736	9.818808	1.306037924
13.283437	9.83519	1.350603025
13.276254	9.830311	1.350542627
13.130203	9.850567	1.332938841
13.374419	9.826915	1.360998759
17.664959	9.845161	1.79427825
15.107874	9.795667	1.542301751
14.279455	9.858708	1.448410441
15.239559	9.855649	1.546276489
14.550008	9.817151	1.482100926
13.977777	9.822323	1.423062209
14.042421	9.833206	1.428061294
14.736761	9.836937	1.498104688
12.720782	9.834756	1.293451726

12.565154	9.771634	1.285880532
20.389645	9.697644	2.102535885

Table C2 Path 2

Maximum	Average	Maximum/Average
14.023268	9.830386	1.426522571
23.236437	9.813716	2.367751163
16.405571	9.843785	1.666591762
21.112715	9.934406	2.125211565
22.910816	9.750078	2.349808499
19.206873	9.839339	1.952049116
33.462383	9.933985	3.368475136
23.217283	9.805459	2.367791475
16.458244	9.817777	1.676371779
16.503736	9.812124	1.681973871
26.358572	9.801839	2.689145448
21.414394	9.872715	2.16904802
22.28591	9.801508	2.273722611
32.143139	9.809793	3.276638011
14.44466	9.861241	1.464791361
20.169371	9.818072	2.054310673
13.530047	9.837458	1.37536008
15.299416	9.844016	1.554184454
25.137491	9.869195	2.547065988
13.589904	9.817591	1.384240257
13.146963	9.825679	1.338020776
12.380795	9.837599	1.258517962
12.737542	9.836483	1.294928419
14.111856	9.834509	1.434932508
14.432689	9.810909	1.471085847
13.494133	9.84678	1.370410777
14.727184	9.852171	1.494816088
13.103866	9.816854	1.334833549
12.835708	9.834888	1.305119869
13.728772	9.847467	1.394142482
13.369631	9.828525	1.36028871
16.726404	9.843128	1.699297685
14.016085	9.834845	1.425145537
14.351283	9.827313	1.46034666
15.083931	9.84088	1.532782739
13.745532	9.816517	1.400245362
12.866833	9.779386	1.315709763

Table C3 Path 3

Maximum	Average	Maximum/Average
13.525258	9.822255	1.377001294
16.178114	9.773334	1.655332198
14.652962	10.02133	1.462177361
15.215616	9.865089	1.542369878
15.99615	9.718993	1.645864877
29.61718	9.879548	2.997827457
32.693821	9.760829	3.349492092
18.316202	9.835433	1.862266877
17.164557	9.822503	1.747472786
21.368902	9.832361	2.173323617
27.61796	9.858856	2.801335111
19.932339	9.804102	2.033061187
19.697699	9.856407	1.998466538
37.40815	9.834954	3.803591619
15.639403	9.819326	1.592716542
13.692858	9.811459	1.395598521
14.966612	9.86978	1.51640781
41.634045	9.764959	4.263616984
16.230789	9.887986	1.641465659
13.293014	9.831643	1.352064302
13.223579	9.830699	1.345131067
13.259494	9.798215	1.353256118
13.005701	9.838958	1.321857603
14.612259	9.865257	1.481183879
13.175694	9.836038	1.339532606
13.233157	9.816837	1.348006161
15.110269	9.817374	1.539135495
13.429487	9.845105	1.364077526
14.52846	9.826373	1.478517027
13.597087	9.819474	1.384706316
12.821342	9.818126	1.305884802
12.589097	9.840284	1.279342833
13.63779	9.849566	1.38460828
12.77585	9.837772	1.298652781
13.544413	9.837739	1.376781139
14.561979	9.824758	1.482171848
12.277842	9.807142	1.251928591

Data collection on the stretch in Linköping measured with the Gocator laser sensor 2375A-3B-N-11. The sensor registered the profile consistently over a width of 520 mm. The measurements were recalculated by zeroing the horizontal profile and for every 5 meters, divide the maximum with the average value. Figure C1 shows the result from the calculation, based on the measurement on Path 1. The result in Figure C2-C4 are based on the measurements on Path 2 and Figure C5 is based on Path 3.

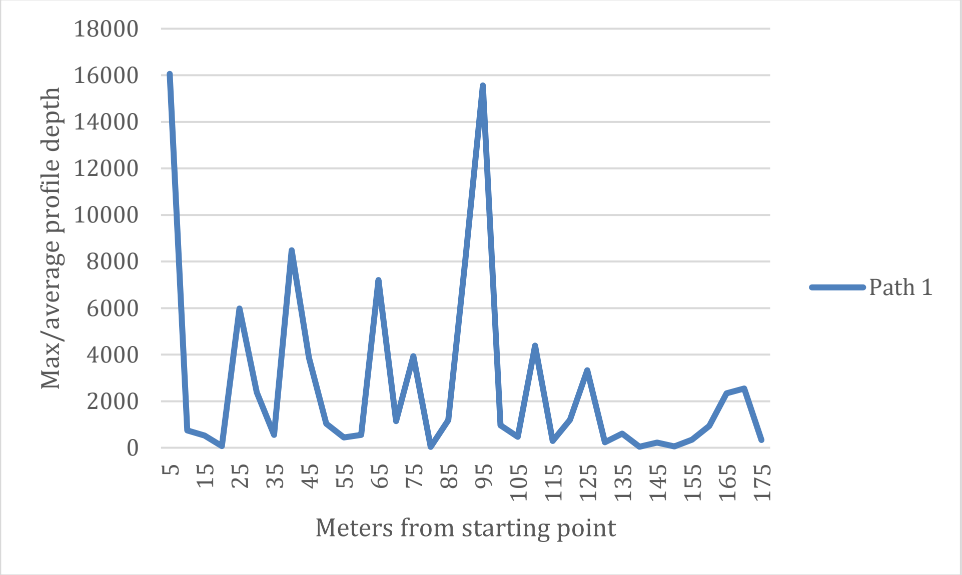

Figure C1 Measurements Path 1

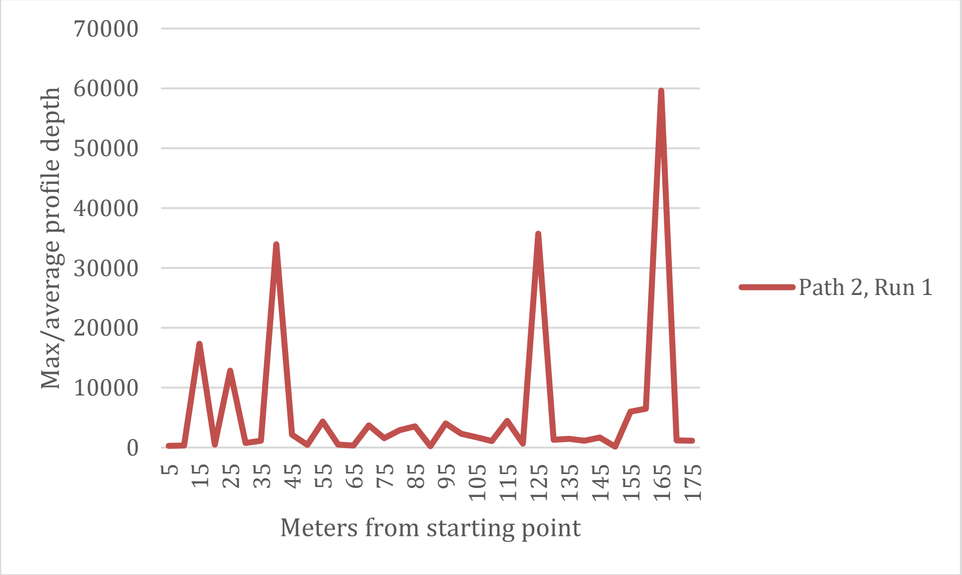

Figure C2 Measurements Path 2, Run 1

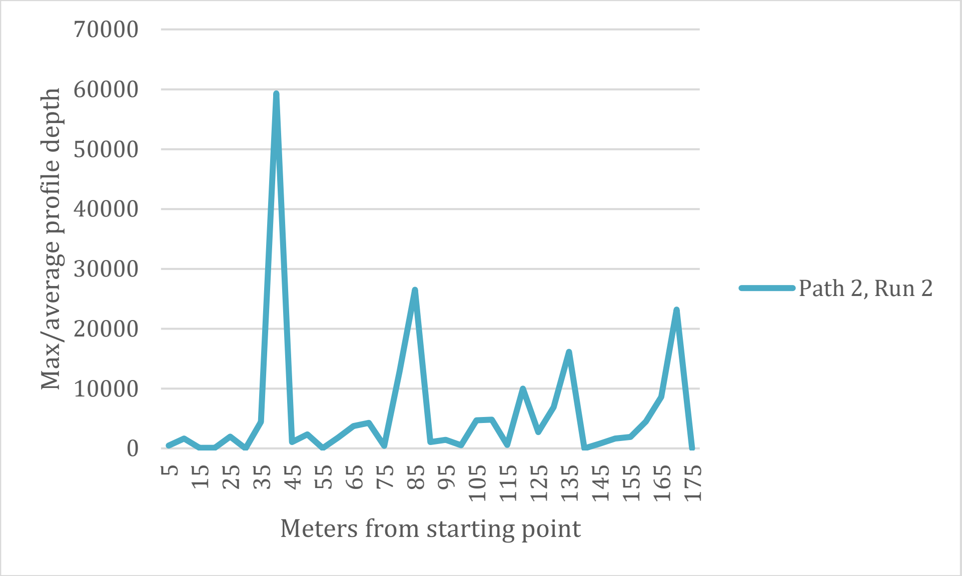

Figure C3 Measurements Path 2, Run 2

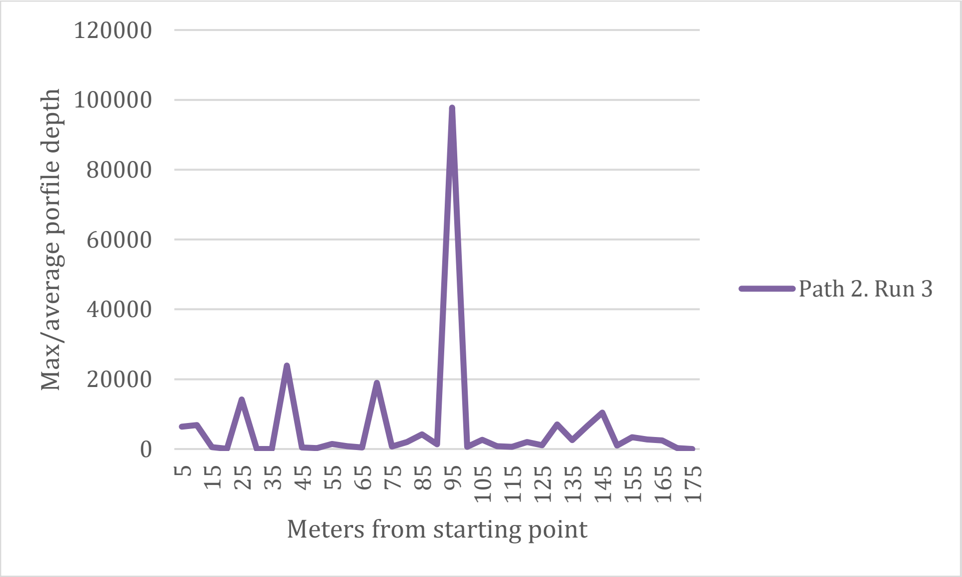

Figure C4 Measurements Path 2, Run 3

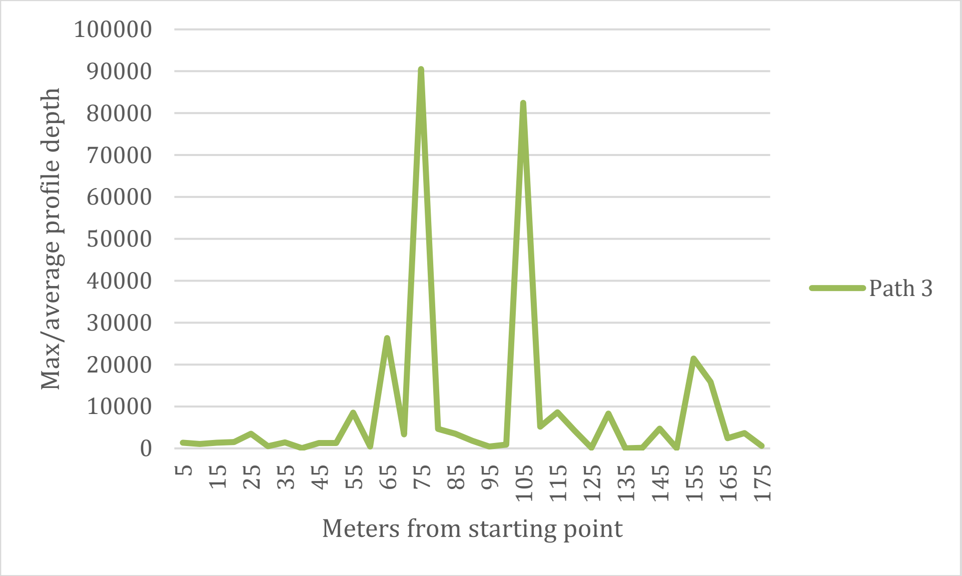

Figure C5 Measurements Path 3