Definition of indicators for the assessment of the structural condition and riding comfort of cycle paths

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Abstract. In recent years, the importance of the bicycle for everyday mobility has increased significantly in Germany. In order to increase the attractiveness of cycle traffic, the provision of safe cycle paths in a good structural condition is necessary in addition to the expansion and new construction of cycling infrastructure. Against this background, the Federal Ministry of Digital and Transport has been funding the research project "Recording and Assessment of the Structural Condition of Urban Cycle Paths" since September 2021. In cooperation with Schniering GmbH and the engineering office Feiler und Hänsel GbR, the University of Applied Sciences Aachen is working on the development of a suitable measurement and assessment procedure. The methods used so far in Germany to record and assess the condition of cycle paths are very much based on the established methods for road condition monitoring and assessment. However, the damage characteristics on cycle paths as well as their effects on road safety aspects, riding comfort and structural value preservation can only be compared with roads to a somewhat limited extent. For this reason, extensive structural assessments of cycle paths were carried out in the research project and a damage catalogue was developed for the recording and assessment of the condition of urban cycle paths. The relevant types of damage are assigned to the following characteristics groups: unevenness, rolling resistance, substance characteristics and vegetation. Based on the results, requirements for the measurement technology and its accuracy could be defined. The conceptual design of a measuring vehicle by the project partner Schniering GmbH will be completed this year and its use tested on various urban cycle paths.

1 Introduction

The importance of the bicycle for everyday mobility has increased significantly in Germany over the last 15 years. This is, for example, shown by the analysis of cycling traffic published in 2019 by the Federal Ministry of Transport as part of the study "Mobility in Germany" [1]. Today, some 80% of all households in Germany own at least one bicycle, which amounts to

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about 78 million bicycles. The volume of traffic has increased by about 13%, and traffic performance by as much as 37% [1].

Urban cycle paths constitute a considerable public asset, so that in terms of operational and structural maintenance, economic value preservation is of great importance. At the same time, a high-quality cycling infrastructure is the essential basis for attractive cycle traffic. In order to be able to meet these tasks and the increasing demands of users, the involved administrations in the districts, cities and municipalities require data-based planning tools.

In the area of federal trunk roads, the monitoring and assessment of road conditions with high-speed measuring vehicles has been carried out regularly in Germany for more than 25 years. The processes and sequences of operations are standardised in the ZTV ZEB-StB [2]. There are still no standards for urban cycle paths in Germany. In some federal states, the condition of cycle paths has already been recorded, but these are based on different recording technologies and different assessment methods. For the most part, they are based on the system used to record the condition of roads. However, this does not do sufficient fit to the characteristics of the damage occurring on cycle paths. For this reason, the current research project [3] is defining condition indicators and recording parameters for monitoring the condition of urban cycle paths and developing a suitable recording technology for this purpose.

2 Recording the condition of urban cycle paths

The research on previously used methods of recording and assessing the condition of cycle paths has shown that different recording methods are used nationally and internationally. In principle, these can be divided into “visual” and “measuring” recording methods.

2.1 Visual Recording of Condition

With the visual recording method, the damage on cycle paths is surveyed by trained personnel during a walk and visual inspection. The detected damage is entered into a prepared input mask on a PC tablet and then evaluated.

A further development of the visual recording method is the visual-image-based recording of the condition. For this purpose, inspection bicycles are equipped with suitable camera technology in order to ride along the cycle paths. The damage is evaluated in post-processing on the basis of the image or video recordings [4, 5].

In the context of further research work, alternative methods for recording the condition have also been developed. One example is “Crowdchupa, Vaisala and Sirway” by the company AFRY [6]. The residents of various cities in Finland were called upon to record the structural condition of the cycle paths with the help of apps installed on their smartphones (so-called crowdsourced road asset management). The data from the video recordings were collected centrally. With the help of AI-based software, the surface damage is to be detected automatically. The aim is to get information on the current structural condition based on rapid data availability and to quantify the damage in defined surface sections [6].

2.2 Measuring Recording of Condition

In addition to the visual recording of urban cycle paths, methods using measuring equipment are used for recording in order to assess the usability and structural condition. Measuring bicycles and measuring vehicles equipped with sensor and camera technology are used here, with different technology setups in each case.
2.2.1 Measuring bicycles

In Germany, the first measuring bicycle for recording the condition of cycle paths was developed by the University of the Federal Armed Forces in Munich in 2005 [7]. The measuring bicycle was equipped with an acceleration sensor to enable the riding comfort to be described on the basis of the vertical accelerations determined. Videos, GPS tracks and sound signals were recorded at the same time. The accelerometer was attached to the front axle and a camera to a tripod, in extension of the front axle. This measuring bicycle was used to record the condition of cycle paths on state roads in the federal states of Schleswig-Holstein and Brandenburg [7].

In the context of another research project, a measuring bicycle for recording the condition of cycle paths was developed at Edinburgh Napier University [8], which was equipped with a camera and an accelerometer. In order to quantify the effects of existing unevenness on the riding comfort while cycling, the standard BS EN ISO 5349-1:2001 [9] from the field of occupational health and safety was consulted and threshold values for permissible vibrations were derived from it. In a research project at the Swedish Cycling Research Centre, an alternative measuring recording system, based on a measuring bicycle was developed [16]. It was decided to use a measurement trailer pulled by a bicycle, which was also equipped with measurement technology (a front camera for instance). In addition, an accelerometer, a GPS antenna, a reflective sensor and a transverse road profile scanner (Gocator 2375) were used to record the condition of cycle paths [16].

2.2.2 Measuring vehicles

In the Netherlands, measurement technology has been used for more than 20 years to record the condition of cycle paths. Fig. 1 (left) shows the Fietscomfortmeter (FCM) from Kiwa KOAC B.V. [10]. It consists of a vehicle with a longitudinal evenness measurement system, a camera system and a GPS receiver. Two high-speed road profilers (HSRP) are mounted on the back of the FCM at a distance of 0.8 m from each other. This corresponds to the distance between two cyclists riding side by side. The HSRP consists of a laser distance sensor and an accelerometer. The longitudinal height profile of the roadway is recorded in the wavelength range of approx. 0.2 to 20 m. The surface damage (e.g. cracks, spallings) is recorded visually by the driver using a tablet PC [10].

The measuring vehicle from Schniering GmbH (see Fig. 1 right) is equipped with laser distance sensors for recording the longitudinal height profiles in the right and left wheel tracks according to the principle of multiple sampling in accordance with ZTV ZEB-StB [2]. The measuring beams are 2.0 m long and record the longitudinal height profiles in lines in the wavelength range from approx. 0.2 to 20 m [3]. The recorded longitudinal height profile of the cycle path forms the basis for the subsequent determination of parameters for the assessment of longitudinal evenness. Furthermore, the measuring vehicle has a front camera, surface camera with artificial lighting, rear camera as well as GPS and distance measurement. Subsequent image evaluation of the front, rear and surface cameras is done manually. In Germany, the measuring vehicle was used to record the condition of cycle paths in the City of Lübeck as well as on cycle paths on state roads in North Rhine-Westphalia, Lower Saxony and Baden-Württemberg [3].
In conclusion, it can be said that the range of methods currently used for recording the condition of cycle paths is very broad. The measuring recording methods determine different parameters, making it almost impossible to make statements on the comparability of the methods. So far, no technical quality parameters such as sampling rates, recording widths, pixel sizes, resolution, image quality, etc. have been defined for the methods used in Germany to record the condition of cycle paths. However, this is required for the comparability of the methods and the provision of high-quality data for assessing the condition of cycle paths. Against this background, the measurement technology is being further developed in the current research project [3]. In order to be able to define the necessary features of the measuring equipment including the quality requirements, the characteristic damage on cycle paths and its extent as well as its relevance for operational and structural maintenance measures must be identified.

3 Indicators for describing the condition of cycle paths

In order to determine the relevant condition indicators for describing riding comfort, road safety aspects and the structural condition of urban cycle paths, the current research project [3] carried out structural assessments on various cycle paths, among them those in the Aachen city region. For this purpose, asphalt and paved cycle paths of different ages were selected for damage assessment on sections between 400 and 800 m in length. The individual damages were measured with regard to their extent and geographical location. The height differences for longitudinal and transverse unevenness were measured with a 2-metre straight edge. The detected cracks were recorded in terms of their length and their maximum crack width. The affected surface area was established for all damages. Texture measurements were carried out to determine the surface roughness. In addition, the possibilities of using photogrammetry and laser scanning for recording surface damage on a section of 800 m were studied. The aim of the research was a classification of the damage typical for cycle paths and the creation of a damage catalogue for the measuring recording of the condition. Based on the existing damage characteristics and their relevance for the assessment of riding comfort, road safety aspects and structural condition, a suitable measurement technology is to be selected and the required accuracy of the measurement technology for recording the individual parameters is to be determined.

3.1 Characteristics group: Unevenness

Uneven surfaces are geometric irregularities of the road surface that cannot be attributed to the texture or the gradient of the route. They are height deviations from the intended surface
A very frequent type of damage on asphalted cycle paths are wave-like uneven sections caused by root uplifts (see Fig. 2 left). During the structural assessment, height differences between \( \leq 20 \text{ mm} \) up to approx. 80 mm were recorded. Fig. 2 (right) shows the distribution of the maximum height differences of the recorded uplifts on the examined cycle paths. The largest proportion (52\%) is made up by root uplifts between 20 mm and 40 mm. The share of uplifts above 40 mm up to a maximum of 60 mm amounts to 26\%. Uplifts with a maximum height difference of more than 60 mm were detected in 3\% of the cases. Furthermore, it was observed that very often cracks occur along the root uplift (see Fig. 2 left), which causes, or may cause progressive damage development.

Root uplift causes considerable unevenness on paved cycle paths, with predominantly impact-type edges forming here due to offsetting and displacement of the paved elements or slabs. In the process, height differences ranging from 10 mm to 30 mm occur. The bond of the fastening elements is often disturbed.

All in all, unevenness is a very relevant condition characteristic for the assessment of riding comfort and road safety aspects of cycle paths. They are to be recorded during the measuring recording of the condition. The required recording accuracy should be \( \pm 5 \text{ mm} \).

![Fig. 2](image)

Fig. 2. Typical damage caused by root uplift on an asphalted cycle path (left) and determined maximum height differences due to unevenness (right).

When recording the condition of cycle paths, line-based laser systems are currently mainly used for recording the longitudinal evenness. Transverse unevenness data have not yet been recorded on cycle paths [see 3, 11]. The unevenness on cycle paths, however, forms in longitudinal and transverse directions as a result of natural root growth, typically in the form of waves. Therefore, recording the unevenness on only one measuring line provides insufficient information. With the help of a 3-dimensional depiction of the cycle path's surface, much more realistic geometric images could be obtained. Today, methods of photogrammetry and laser scanning are available in surveying, with which 3D images of the surface can be generated and detailed height information obtained. Within the framework of a Master's thesis, a measurement was done on a section of the cycle paths being examined using photogrammetry by drone (DJI Phantom 4 RTK drone) and, at the same time, a site-based Trimble SX10 laser scanner. The aim was to find out the possible areas of application of these technologies as well as their limitations for recording the condition of cycle paths using measuring recording technology [12].

Fig. 3 (left) shows a damaged area captured by photogrammetry. Due to the dense point distribution of the point cloud section and the height colouring, detailed information on the existing height differences is provided in addition to the visualisation of the damage spread. These can be important indicators for the assessment of the damage and the necessary structural maintenance measures. In comparison, Fig. 3 (right) shows the same damage site, recorded with a laser scanner. Although the 3-dimensional depiction is considerably less detailed due to the significantly lower point density, the extent of the damage and the information on the existing height differences are also provided by the height colouring.
Fig. 3. 3D depiction of a damaged area based on point distribution and height colouring using photogrammetry (left) and laser scanner (right) [12].

It seems that, as a general rule, both technologies are suitable for recording the unevenness of cycle paths. Disadvantages caused by shadows or changing light intensities outdoors are currently being studied as part of the project [3] with the aim of identifying a suitable measurement technology.

3.2 Characteristics group: Rolling resistance

Rolling resistance plays a major role in cycling, as it influences the effort required. From a physics point of view, rolling resistance corresponds to the decrease in kinetic energy that is lost when the tyre rolls on the road surface. The energy dissipation results mainly from the continuous material deformation in the tyre. The following applies to the rolling friction force FR [13]:

\[ F_R = \mu \cdot F_N \] (1)

with:
\( \mu \): as rolling friction coefficient
\( F_N \): as magnitude of the normal force

The rolling friction coefficient \( \mu \) depends on the materials (tyre, roadway) and their surface. Surface properties of the roadway such as skid resistance and rolling resistance are determined by the texture. A distinction is made between micro, macro and mega texture. The correlation between the surface texture of cycle paths and the influence on rolling resistance has not yet been examined in detail. In order to gain some initial insights, texture measurements were carried out in accordance with TP Textur-StB (ZTM) [14] and the MPD value (Mean Profile Depth) was determined. The MPD value describes the macro texture of the road surface to characterise the roughness.

Fig. 4 shows the results of the texture measurements on an asphalted cycle path and a cycle path that was coated red in 2021 for better identification. Epoxy resin was used for the coating, which was sprinkled with an aggregate with diameter of 1-2 mm. For better comparability of the results, the MPD values determined were divided into classes. In the range between 0.46 and 0.66 mm, both cycle paths exhibit the largest proportion of the MPD values determined. It is recognisable that the range of recorded MPD values is considerably larger on the asphalted cycle path. The surface texture of this cycle path is clearly more heterogeneous when compared to the surface texture of the coating.
The lower the macro texture, the smoother the surface and the lower the rolling resistance, which has a positive effect on riding comfort. On the other hand, the tyre of the bicycle should have good adhesion (interlocking) to the surface in order to be able to transmit the tractive, braking, cornering and steering forces. In order to define requirements for the texture of cycle path surfaces that ensure both low rolling resistance and good grip, further research is planned.

The macro texture of the cycle path surface is a relevant condition characteristic for the assessment of riding comfort and road safety aspects of cycle paths and should be included in the measuring recording. It is proposed to use a triangulation laser, which allows the determination of four MPD values per measuring metre according to [14].

3.3 Characteristics group: Substance characteristics

Within the characteristics group “Substance characteristics”, the condition characteristics are to be categorised according to the construction method. In the research project [3], the construction methods most often used on cycle paths in Germany, which are asphalt and paved surfaces, were examined. As a result of the structural assessment, cracks (longitudinal cracks, transverse cracks, net cracks), open seams and joints, patches as well as spallings, breakouts and thinnings were defined as relevant condition characteristics of asphalt surfaces. On paved surfaces, a distinction is made between damaged paved/slab elements, open paved/slab joints as well as patches and disturbance in the bond and joint design for the relevant condition characteristics. Substance characteristics for cycle paths built with the asphalt construction method is presented in the following as an example.

3.3.1 Cracks

The assessment revealed condition characteristics due to cracking: There are longitudinal and transverse cracks as well as net cracks (see Fig. 5).
The longitudinal and transverse cracks depicted constitute serious structural damage to the cycle path, requiring action for structural maintenance measures. During the assessment, it was observed that transverse cracks often occur across the entire width of the cycle path. This suggests that an old concrete pavement or a hydraulically bound base course has been overlaid and that the cracks have penetrated upwards. The longitudinal cracks, observed within the structural assessment, indicate subsidence in the subsoil.

Fig. 6 shows the distribution of the determined maximum crack widths of longitudinal and transverse cracks in the cycle paths inspected in the Aachen city region. About 55% of the longitudinal and 57% of the transverse cracks show crack widths of 10 mm or smaller. Crack widths in the longitudinal direction of 20 mm or more can have a negative impact on road safety aspects. Occasionally, crack widths of more than 40 mm (longitudinal cracks) and 60 mm (transverse cracks) occur.

Besides longitudinal and transverse cracks, net cracks (Fig. 5, right) were detected. They often occur where cycle path drainage facilities such as gutters, drains or swales are no longer functional and the run-off of rainwater is no longer guaranteed.

In addition, net cracks in the near-surface area of asphalted cycle paths were also found during the structural assessment. Fig. 7 shows examples of such cracks on an approximately 10-year-old cycle path. The crack widths range from 1-2 mm and are only a few millimetres
deep. Weather-related material fatigue has led to these crack formations and superficial weathering. From the point of view of road safety and structural value preservation, this damage is not critical and does not need to be detected while recording the condition.

![Image of cracks in the near-surface area on an asphalted cycle path.]

**Fig. 7.** Net cracks in the near-surface area on an asphalted cycle path.

All in all, cracks are a relevant condition characteristic in the assessment of the structural condition of cycle paths and must be included in the measuring recording. According to ZTV ZEB-StB [2], crack widths of 1 mm or more must be detected with high-speed measuring systems during road condition recording in Germany. This accuracy is not required for the condition recording on cycle paths, neither for the assessment of the basic structure nor for reasons of riding comfort and road safety aspects. Based on previous findings, crack widths of 5 mm and more should be recorded and assessed.

### 3.3.2 Further substance characteristics on asphalt construction

In the course of the structural assessments, further substance characteristics, such as open joints and seams, patches, spalling’s, breakouts and thinning’s, were detected on asphalt cycle paths alongside cracks. Breakouts occur as a result of material fatigue, wear or frost action. They were predominantly found in combination with cracks and uplifts.

Patches caused by excavations during corrective maintenance and modernisation work on the existing supply and disposal facilities are typical for urban cycle paths. If the work is done professionally, no damage will be found here. Often, however, the assessment revealed that the patching had not been carried out properly. In addition, open seams and joints in the longitudinal direction, in particular, constitute a condition characteristic relevant to road safety aspects.

In the case of cycle paths with a coating or an applied thin layer pavement, damage can occur due to the surface layer detaching from the underlying layer. Depending on the age of the pavement and the load, these spalling areas can range from small to large. From the point of view of structural value preservation and road safety, they are relevant and must be detected in the course of measuring recording.

When recording the condition of cycle paths, the substance characteristics should be documented using camera technology.

### 3.4 Characteristics Group: Vegetation

Other very typical condition characteristics on cycle paths are green growth on the cycle path surfaces as well as green growth in the clearance gauge. This vegetation related
characteristics are relevant for the assessment of riding comfort and road safety aspects. Green growth that spreads on the surface of cycle paths, or from the edge area, leads to a reduced available cycle path width. Green growth in the clearance gauge leads to non-compliance with the basic planning measurements and requirement for traffic and safety spaces according to ERA [15]. Fig. 8 shows an example of a cycle path that has vegetation both on the surface and in the clearance gauge. The measured width of this cycle path is 2.50 m and the required height of the clear space is 2.50 m according to [15]. Both values are not complied because of the green growth and are therefore relevant for road safety aspects.

![Fig. 8. Example of vegetation on the surface and in the clearance gauge of a cycle path.](image)

### 4 Assessment of condition indicators

Table 1 lists all relevant characteristics groups, condition characteristics and condition indicators that are to be included in the assessment of condition of urban cycle paths. One example for condition indicators: when it comes to the evaluation of the recorded condition characteristic "cracks", the percentage of the surface area affected, the length dimension and the maximum crack width must be determined.

With the help of an assessment procedure, a determination must be made - what level of severity or frequency, resp., of the ascertained damage is likely to have a negligible, a weak, a medium, a strong, or a very strong, effect. From this, the need for further action must be defined. In the current research project [3], a proposal is being developed that includes the formation of the values "Riding Comfort", "Road Safety Aspects" and "Structural Condition". In order to enable a mathematical linkage of several condition characteristics, the determined condition indicators get transferred into non-dimensional condition values.
To indicate a poor condition of the cycle path and, accordingly, a need for preservation, warning and threshold values are developed for the individual condition characteristics. In the assessments of cycle paths carried out in Germany so far, existing requirements from road condition recording have been adopted for the most part. However, for the derivation of preservation measures, the requirements of the cycle paths are decisive: In addition to the assessment of damage processes on cycle paths, cycling dynamics considerations should also be included in order to better assess the riding comfort on urban cycle paths. The different existing assessment approaches as well as already existing requirement values are compiled and examined with regard to their suitability.

Table 1. Overview of characteristics groups, condition characteristics, condition indicators (as of May 2023).

<table>
<thead>
<tr>
<th>Characteristics Group</th>
<th>Condition Characteristic</th>
<th>Condition Indicator</th>
<th>Input Variables for Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unevenness</td>
<td>Longitudinal / transverse unevenness (uplifts / subsidence)</td>
<td>Height dimension [mm]</td>
<td>…Riding Comfort</td>
</tr>
<tr>
<td></td>
<td>Rolling Resistance</td>
<td></td>
<td>Road Safety Aspects</td>
</tr>
<tr>
<td>Substance characteristics of asphalt surfaces</td>
<td>Longitudinal cracks, Transverse cracks, Other cracks (e.g. net cracks)</td>
<td>Surface area perc. [%]</td>
<td>…Structural Condition</td>
</tr>
<tr>
<td></td>
<td>Open seams or joints</td>
<td>Length dimension [mm]</td>
<td>Road Safety Aspects</td>
</tr>
<tr>
<td></td>
<td>Patches</td>
<td>max. opening width [mm]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spallings, breakouts, thinnings</td>
<td>Surface area perc. [%]</td>
<td></td>
</tr>
<tr>
<td>Substance characteristics of paved surfaces</td>
<td>Damaged paved elements and slabs</td>
<td>Surface area perc. [%]</td>
<td>…Structural Condition</td>
</tr>
<tr>
<td></td>
<td>Open paved and slab joints</td>
<td>Length dimension [mm]</td>
<td>Road Safety Aspects</td>
</tr>
<tr>
<td></td>
<td>Disturbance in the bond and joint design</td>
<td>max. opening width [mm]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Patches</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetation</td>
<td>Green growth on cycle path surface</td>
<td>Surface area perc. [%]</td>
<td>…Road Safety Aspects</td>
</tr>
<tr>
<td></td>
<td>Green growth in clearance gauge</td>
<td>existent yes/no</td>
<td>Riding Comfort</td>
</tr>
</tbody>
</table>

5 Equipment of a measuring vehicle

The definition of condition indicators and quality parameters form the basis for the selection and design of the recording technology. In the research project [3], a fully electric narrow-gauge vehicle was selected, which is very well suited for driving on urban cycle paths due to its dimensions and manoeuvrability.

The recording of the route images is done with a front and a rear camera. Via control of a trigger system, both cameras simultaneously, and independent of the measuring speed, record one image for each measuring metre. The recording of surface damage is done with an area scan camera, which also captures one surface image for each measuring metre. The uniform illumination of the cycle path surface is ensured by four stroboscopes.

An INS system (Inertial Navigation Satellite System) is installed for continuous recording of the vehicle position during the measurement run. The recording of the macro texture is carried out with a high-precision triangulation laser, which determines four MPD values per measuring metre.

The unevenness is to be determined on the basis of detailed height information by means of 3D mapping of the surface over the width of the cycle path. Different photogrammetry and laser scanning techniques were tested as part of the project.

The implementation of a suitable technique in the measuring vehicle will completed before the end of the year.
6 Conclusion

Up to now, there are no defined standards for the recording and assessment of the condition of urban cycle paths in Germany. Based on the findings of the ongoing research project [3], it was possible to define the relevant indicators for the condition recording of urban cycle paths and to develop a suitable recording technique for this purpose. The condition indicators constitute the input variables for the assessment procedure currently being developed, with which the need for action and preservation is to be demonstrated via the values "Riding Comfort", "Road Safety Aspects" and "Structural Condition".

Within the framework of the ongoing research project, the new measuring vehicle is being used on pilot routes and the condition of these course sections is being assessed. The findings obtained in [3] will be incorporated into a municipal guideline. In further research work, the assessment methodology is to be further developed and validated on the basis of cycling dynamics investigations and test person studies. By examining the aspects of cycling dynamics, a user-oriented assessment is carried out with the aim of providing cyclists with a permanently reliable and high-quality cycling infrastructure.

Acknowledgments

The Federal Highway Research Institute in charge of Federal Ministry for Digital and Transport supported under Contract No FE 70.0957/2019 this work. The authors would like to thank the agency and ministry for their research support.

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