Comfort evaluation of new bicycle paths with a laser profilometer: 15 years of experience in Belgium

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Abstract. Longitudinal evenness of a road or bicycle lane surface is important for users’ comfort. For roads, indicators for evenness, their relation to users’ comfort in cars or trucks, and acceptance levels for existing or newly constructed roads exist for decades. In Belgium, four indicators called “Evenness Coefficients” (EC) are in use. Considering the surface as a wave, each EC evaluates a different range of wavelengths. EC0.5, for the shortest wavelengths, was introduced in 2013 by the Flemish National Road Administration (Fl-NRA). In 2013/2014 two measurement devices dedicated to longitudinal evenness evaluation of cycle infrastructure were put in service. Fl-NRA set requirements for roughness on new bicycle lanes expressed in EC0.5 and EC2.5 and uses a combined indicator for the evaluation of the global condition of their bicycle lane network in two-year intervals. The Belgian Road Research Centre (BRRC) helped investigating the potential causes in cases where the requirements were not attained. This contribution reports on more than a decade of experiences with dedicated measurement devices, on factors influencing users’ comfort of bicycle infrastructure, and on the “comfort score” obtained from a less costly “measuring bike”. The article concludes addressing perspectives on European standardisation actions for roughness measurements on bicycle infrastructure.

1 Introduction

In recent years investments in cycling infrastructure by road management organisations is steadily increasing. The comfort of the bicycle lane surface is an important factor for the attractiveness of cycling infrastructure so that it would be effectively used. Comfort is a functional expectation of the bicycle lane users and is related to the vertical accelerations felt by the users when driving over the bicycle lane. Several devices were designed and implemented where a bicycle or other vehicle is equipped with an accelerometer measuring the response generated by the unevenness of the bicycle lane. In Belgium, the Fietsersbond – a representative body of cyclists – started using an early version of their “comfort bike” in 2007. Today the comfort bike is equipped with an accelerometer on a third wheel towed by a bicycle and with a tablet for the registration of information on the infrastructure, and the

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Belgian Fietsersbond performs systematic measurements with it, commissioned by bicycle lane managers.

Bicycle path managers are confronted with the question what the technical specifications of a comfortable bicycle lane are and how they can be evaluated. Longitudinal (un-)evenness of the bicycle lane surface is an important cause of (un-)comfort. Hence, bicycle lane managers feel the need for a measurable, technical indicator, expressing the longitudinal evenness of the bicycle lane surface. In Belgium, the Flemish National Road Authority (NRA) addressed this issue already more than 10 years ago. Indicators and criteria were developed, the Flemish NRA and BRRC invested in a dedicated measurement device, newly constructed bicycle lanes must respect thresholds which are verified with the device, and the Flemish NRA used its device for systematic quality assessment of the bicycle lane network under their responsibility.

In the following, the definition of the family of indicators called “Evenness Coefficients” (EC), currently primarily used in Belgium, will be given and the use of the different family members for road and bicycle lanes will be discussed. Two family members are used for bicycle lanes: EC0.5 and EC2.5.

The “bicycle path profiler” (BPP) is laser profiler specifically designed for bicycle lanes and in use in Belgium for more than a decade for the determination of EC0.5 and EC2.5 is presented, as well as the thresholds applied for tenders for new bicycle lanes in Flanders. The quality of the measurement device is addressed as well.

The technical factors influencing the longitudinal evenness of bicycle lanes are discussed. Some factors are related to the design of the infrastructure, other factors are related to the execution phase and the materials used for the realisation of the surface.

Other measurement devices exist and are in use, some of which report an evaluation of comfort. Comparative studies were made between two such devices and the BPP and the results are presented briefly.

The BPP was used by BRRC for two other applications not directly related to bicycle lanes. These two experiments are also presented. In the first experiment the BPP was used for the evaluation of unevenness at manholes present in the surface of road pavements. In the second experiment the “structural index” for the pavement management system approach proposed by BRRC for communal road networks was determined by data collected by the BPP.

### 2 Evenness coefficients

The evenness coefficients (EC\(B\)) are a family of indicators that express the evenness of road surfaces ([1]) and bicycle lane surfaces. Each member EC\(B\) of the family depends on the value of parameter B. In Belgium, for roads, the three members with B = 2.5m, B = 10m, and B = 40m are used. For bicycle lanes, the members with B = 0.5m and B = 2.5m are used in Flanders, Belgium. When the evenness of the surface of a road or bicycle lane section is measured with a “class 1” profiler device, the evenness coefficients can be computed and are reported on segments of length E. From a theoretical standpoint, E must at least be 2.5 times B. In practice, the choice for E is usually made between E = 10m, 25m, 100m, or 400m. For bicycle path surfaces, E = 25m is most commonly used.

The evenness coefficient is a measure for the surface between two curves. The first curve is the output of the profiler device: a representation of the line measured on the surface while driving over the road or cycle lane, usually in the wheel path of the ordinary users. The profiler device used for this purpose typically acts as a filter. A road or bicycle lane surface can be seen as a wave that can be decomposed per wavelength by a Fourier transform. The “very long” wavelengths in the road or bicycle lane profile are not measured: the profiler device does not measure the glowing of the surface of the Earth. Similarly, the “very short”
wavelengths are not measured either: the profiler is not meant for measuring the texture of the surface. The representation of the first curve is discrete, by a large number of points \((x, A(x))\). These points are equidistant on the X-axis of the travelled distance by the profiler device. The second curve is computed from the first one. Over a distance \(B\), the average of all measured points is computed, giving rise to a point \((x, A_g(x))\) of the second curve. By sliding over the first curve, the averages form the second curve of “sliding averages”. For the computation of the sliding average, some points before the beginning of the segment and some points after the end of the segment are used as well. Standard measurement procedures for profiler devices foresee that the measurements start well before the beginning of the road or bicycle lane section to be monitored and continue well further than the end of the section.

The evenness coefficient \(EC_B\) is reported on consecutive blocs of length \(E\). The first of these blocs starts at a distance \(x_0\) from the start position of the measurements. With a sliding average technique, the measured longitudinal profile \(A(x)\) gives rise to a flattened profile \(A_g(x)\), defined by equation (1):

\[
A_g(x) = \frac{1}{j+1} \sum_{k=0}^{j} A(x - \frac{B}{2} + k \cdot l)
\]

for \(i = 1, 2, \ldots, N\) and \(j = \frac{B}{l}\) and \(l\) the distance expressed in mm between two consecutive stations in the measured longitudinal profile, \(A(x)\) expressed in mm. For the \(n\)-th bloc of length \(E\) expressed in m, \(EC_B\) is computed with equation (2):

\[
EC_B = \frac{1}{2} \cdot \left( \sum_{x=x_0+(n-1)E}^{x_0+nE} \left| A(x) - A_g(x) \right| \right) \cdot \frac{l \cdot 100}{E} \cdot \frac{1}{1000}
\]

The evenness coefficient \(EC_B\), expressed in \(10^3\) mm²/hm (or \(10^4\) mm²/km), is rounded to 1 decimal place.

When \(B\) is small, the two curves will stay close to each other and the area between them will be due to the small wavelengths in the measured profile. With a large value for \(B\), the two curves will be further away from each other and the contribution of the unevenness due to small wavelengths will become insignificant with respect to the unevenness due to greater wavelengths. So, for bicycle lanes, \(EC_{0.5m}\) will be an objective criterion for very local unevenness primarily impacting on safety, and \(EC_{2.5m}\) will be a measure for longer wave unevenness mainly impacting on comfort.

Which wavelengths really matter to a user, depend on the speed with which the user moves over the surface. Indeed, what matters to the user is the frequency \(f\) generated by the existing wavelength \(\lambda\), which depends on speed \(v\): \(f = \frac{v}{\lambda}\). Therefore, large values for \(B\) are used for the evaluation of roads. In order for a given wavelength \(\lambda\) to be evaluated by a member of the family of evenness coefficients \(EC_B\), \(B\) must be chosen so that \(B < \lambda < 4B\).

### 3 Measurement device: Laser profiler

Whereas laser profilers are used for quite a long time already for the evenness measurements of roads, no such device was known of for application on narrow bicycle lanes. Also, the APL ([1], [2]), another device used on roads in Belgium, France and elsewhere, and with which the evenness coefficients for roads can be determined, would not be easy to adapt for bicycle lanes. Therefore, the Flemish NRA described technical specifications for a laser profiler unit to be installed in a trailer in the technical annex of a European tender. The trailer is towed by a motorcycle. The tender was awarded to the company Greenwood and the measurement device is referred to by the name “bicycle path profiler” (BPP, [3]). About 1 year after the Flemish NRA, BRRC also purchased a BPP.
Fig. 1. Picture (tractor and trailer) and equipment (sensors, PC, GPS) of the Bicycle Path Profiler device.

A picture of the device and a photo of the equipment of the bicycle path profiler is shown in Fig. 1. The main sensors of the BPP are the accelerometer and the laser. Their combined measurements result in the measured surface profile. The BPP is also equipped with a distance measurement sensor, launching the trigger for the registration of a value A(x) at each increment of 0.03m. A laptop and a GPS system complete the equipment in the trailer.

During the measurements, the operator should try to keep a constant speed of at least 15km/h, preferably 20km/h. A slight variation of the speed does not significantly influence the measurement results, but brisk accelerations and decelerations can.

Comparative tests were organised between the Flemish NRA and BRRC whereby a selection of representative bicycle lane sections was measured at the same time, under the same conditions, one BPP driving right behind the other, in order to minimise the effect of lateral wander and differences in speed between the two measurement devices during the rides. Results showed high reproducibility as illustrated in Fig. 2.

Fig. 2. Illustration of results from the comparative tests between the BPP’s of the Flemish NRA and BRRC.

The BRRC also compared the resulting values for EC_{2.5m} on roads obtained from measurements with the APL and BPP equipment of BRRC and found a very high correspondence ([4]).

In the frame of the Belgian pre-normative research project SuChar-BiLan, currently in progress at BRRC ([5]), a list of measurement devices for longitudinal evenness was drafted by a literature search and an additional inquiry of a selection of experts in the field. In The Netherlands, another laser profiler is used on bicycle lanes, but it can only operate on pavements with a width of at least 1.5m ([6], [7]). In Germany a service with the similar device “ARGUS®-AGIL” is offered too ([8]). A laser profiler was tested in Sweden in 2011
(9]) and later also mounted on a small car ([10]). Some references on laser profilers in the USA are [11] and [12].

4 Requirements and evaluation in practice

Prior to the introduction of requirements for longitudinal evenness by the Flemish NRA and prior to the development of the BPP, a study was commissioned by Benelux Bitume (an association who aimed at providing technical and scientific information on bitumen and its applications), Fietsbieraad (a public knowledge centre for policy on cycling) and VBW Asfalt (an association of asphalt construction companies in the Netherlands), to the Dutch company KOAC-NPC. The report gave clear insights about the question which members of the family of evenness coefficients would be most appropriate for the evaluation of bicycle lanes. KOAC-NPC already had long experience with comfort measurements on bicycle lanes in The Netherlands with their “Bicycle Lane Comfort Measuring Device” (Fietspadcomfortmeter, FCM). In 2008 the FCM used accelerometers mounted on two bicycle wheels towed by a small vehicle. The current version of the FCM is equipped with two lasers fixed at the back of a slim car. The results of the FCM are expressed on a scale that differs significantly from the evenness coefficients. The results presented in the report of the study ([13]) were taken into account by the Flemish NRA in their decision process on the introduction of thresholds for EC0.5m and EC2.5m.

New bicycle lanes are evaluated with respect to thresholds for EC0.5m and EC2.5m. In the current version of the standard specifications for tenders of the Flemish NRA ([14]), there are thresholds for construction works executed with machine processing, and more relaxed ones for construction works executed manually, as shown in Table 1.

Table 1. Acceptance thresholds (maximum values for ECB in $10^3$ mm²/hm on blocs with $E = 25$m) in document ([14]) with standard specifications for tenders of the Flemish NRA.

<table>
<thead>
<tr>
<th>Bicycle paths</th>
<th>EC0.5m</th>
<th>EC2.5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executed with machine processing</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>When at least 10m² in bloc executed manually</td>
<td>30</td>
<td>90</td>
</tr>
</tbody>
</table>

The Flemish NRA executes measurements on newly constructed or heavily maintained bicycle lanes with their BPP for the quality assessment with respect to these thresholds. The Flemish NRA also measures the entire network of bicycle lanes under their responsibility on a two-year basis. Every other year, a report is published with the results of a global condition evaluation of the network, mainly based on the combined indicator defined in function of EC0.5m and EC2.5m. A transfer function is applied to each of the evenness coefficients to transform them in an “evenness index” on a uniform scale in the range of 0 to 5. The transfer functions are S-shaped (sigmoid) curves (details in [15]). The “global evenness index” is defined as the minimum of the two “evenness indices” obtained from EC0.5m and EC2.5m respectively. The sections of the network are classified according to 5 classes from excellent condition to very poor condition.

5 Parameters influencing evenness

Experience shows that several situations and technical conditions have a negative impact on the evenness of bicycle lanes ([16], [17]). Many of the bicycle lanes in Belgium have bituminous, concrete, and block pavements. While block pavements are chosen for aesthetics and for ease of local interventions, the joints do seem to have some negative influence on the evenness. For bituminous and concrete pavements holds that the requirements of the Flemish NRA can be respected when these pavements are paved with paving machinery. However,
when the environment necessitates manual paving, even the in such cases somewhat relaxed requirements of the Flemish NRA are more difficult to fulfil, and more difficult for concrete pavements than for bituminous pavements. Indeed, concrete pavements are placed in a single layer and evenness is extremely difficult to correct, whereas bituminous pavements are paved in 2 or 3 layers which allows small corrections to imperfect evenness at the realisation of each layer.

The presence of manholes or other covers in the bicycle lane always interrupt machining. Changes in the central axis of the bicycle lane, for instance for the avoidance of a bus stop, and changes of the width of the lane complicate smooth automated paving. These situations can only be avoided at the planning stage before the start of the works. However, moving a manhole to another location is often financially prohibited and redesigning the geometry of the public domain is often constrained by the limited space, especially in an urban environment.

A separate bicycle lane is often positioned at a higher level that the road pavement, sometimes at the same level as a sidewalk. When the separate bicycle lane approaches a crossroad road, it is often interrupted: the users must descend a threshold and ascend another threshold again at the other side of the crossroad. This unevenness is uncomfortable and can be avoided at the design phase.

Unevenness can develop over time on existing bicycle lanes. Subsidence can be the result of an ineqation between the occasional presence of heavy vehicles on the bicycle lane and its bearing capacity. This occurs for instance at accesses to private garages, to parking areas around shops and to industrial sites, or at places where heavy vehicles regularly park unauthorised for deliveries. Upward growing tree roots can push the bicycle pavement and can result in transversal cracks and local unevenness. The type of trees and the strength of the base course of the bicycle pavement are determining factors. Local interventions on hidden infrastructure underneath the bicycle pavement, such as sewage and gas pipes, and cables for electricity and fibre networks, give rise to local repairs. These are sometimes less well executed and generally done manually.

6 Comfort and comfort measurements

The longitudinal evenness is a technical property of the bicycle lane surface, and the evenness coefficients are technical parameters. Therefore, the evenness coefficients are attractive to bicycle lane managers such as the Flemish NRA, in their pursuit for high quality technical execution of construction works and for efficient maintenance of exiting cycling infrastructure. The users of cycling infrastructure however express their expectations in a functional way. They indicate that their most important expectations are safety and comfort. Quite often the bicycle lane managers consider that surface distress and longitudinal evenness are adequate technical properties responding to these two user expectations: unevenness with very short wavelengths such as potholes and upward pushing tree roots are signs of safety hazards and unevenness with longer wavelengths influence comfort.

Rather than measuring evenness, some measurement devices are developed for the evaluation of comfort. The list drafted in the frame of the SuChar-BiLan project contains a set of devices that make use of an accelerometer installed on a bicycle ([18], [19]), on a trailer towed by a bicycle ([20], picture on the left in Fig. 3), or on a cargo bike ([21], picture on the right in Fig. 3). Some of these use the accelerometer of an ordinary smartphone ([21], [9], [22]), others use a high-precision measurement instrument ([23]).

Determining a correlation between longitudinal evenness and comfort measurements is not trivial. A few unsatisfying attempts were made to compare the “comfort score” of the “comfort bike” of the Belgian Fietsersbond and the BPP of the Flemish NRA around the time of the introduction of the BPP and even a few years later. In 2021 the Belgian Fietsersbond
(picture on the left in Fig. 3), the company DrivenBy (picture on the right in Fig. 3) and BRRC participated in a comparative measurement test on a few bicycle paths in the Province of Antwerp. The data were further investigated at the University of Oldenburg in the frame of the European project BITS ([24]) and their results were reported in [25].

![Fig. 3. The comfort bike of the Belgian Fietsersbond (left) and the device of DrivenBy (right) during the 2021 campaign.](image)

### 7 Evaluation of unevenness at manholes

Manholes giving access to underground infrastructure are sometimes worked in into pavements. There exist thresholds for the maximal acceptable local unevenness between the cover and the pavement. The verification of the threshold can only be done with static measurements, making use of a profiling sensor on a straightedge. An example of such device is the laser equipment shown in (Fig. 4). The execution of a measurement is not without danger and hindrance to the traffic.

![Fig. 4. Laser profiler on 4m straightedge (equipment at BRRC).](image)

When driving over manholes with the BPP with little hindrance to the traffic, the BPP measurement data show a typical signature at manholes (Fig. 5). The BPP data are not as accurate as the data of static measurements, but with the BPP data one can quickly make a first classification of manholes respecting the thresholds for the maximal acceptable local unevenness. The static measurements can then be limited to the manholes for which the BPP did not give clearance. An experiment by driving over manholes was reported in ([3]).
8 Structural index for pavement management

The BRRC proposes an approach for pavement maintenance management for communal roads ([26], [27]). This approach is based on a visual index expressing the visual condition of the pavement surfaces of the network and a structural index expressing the aging of the road structure. While the visual index for a pavement can be obtained from a visual inspection, several techniques for determining the current value of the structural index of an existing pavement. The original definition made use of longitudinal evenness measurements with the APL. Experience shows that the use of the APL on a whole road network of communal roads is cumbersome and partially impossible. The BPP however can be used everywhere. The use of the BPP for this purpose was evaluated and compared to another approach where the structural index is estimated from the visual inspection data. This study on several networks of communal roads was reported in [28]. The conclusion of the study is double: the BPP is indeed an alternative but occasions an additional investment in the execution of the measurements, whereas the estimated value for the structural index from the already available visual inspection data is sufficiently accurate for pavement maintenance management purposes.

9 Conclusion

The relevance and importance of cycling infrastructure is increasing. Managing the quality of newly constructed and the condition of existing bicycle lanes gets more and more attention of users and cycling infrastructure owners and managers. Users expect comfort and safety and therefore cycling infrastructure managers need measurement techniques, indicators, and thresholds for longitudinal evenness as a technical surface characteristic and for comfort as a functional property. By presenting the experience in Belgium, this contribution shows that measurement techniques, indicators and thresholds exist for the evaluation of longitudinal evenness as a technical support for the effort of the bicycle lane manager to provide comfortable and safe cycling infrastructure. For technical evaluation, the bicycle path profiler device (BPP) is used. It provides the evenness coefficients EC0.5 and EC2.5 as indicators of longitudinal evenness in wavelengths relevant for safety and comfort of users, considering their speed when riding over bicycle lanes. Thresholds on EC0.5 and EC2.5 in use for about a decade for new bicycle lanes are presented, as well as factors influencing the longitudinal evenness. A combined indicator based on EC0.5 and EC2.5 is used by the Flemish NRA for reporting on the global condition of the bicycle lane network they manage. The influence of longitudinal evenness on comfort can be studied by comparisons with other measurement devices reporting in scales of vertical accelerations sensed by a bike riding over the bicycle lane and such results obtained in Belgium were also mentioned in this paper.
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