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How comfortable are your cycling tracks? A new method for objective bicycle vibration measurement

Michal Bíl *, Richard Andrášik, Jan Kubeček

CDV Transport Research Centre, Brno, Czech Republic

A R T I C L E   I N F O

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A B S T R A C T

Cycling comfort consists of several factors. Their relevant values are important in the process of bicycle facility planning. Poor surface pavement quality manifests itself in terms of vibrations of a bicycle. This strongly influences the perception of a cycle track, general cycling comfort and the route choice as well. We introduce dynamic comfort index (DCI) which is capable of objectively describing the vibration properties of surface pavement on a track. The DCI is derived from data gathered when riding a bicycle equipped with a GPS device and an accelerometer. The most common types of devices were selected to make the DCI widely applicable. We tested DCI values on various bicycles and surface pavements. DCI values on individual cycling tracks were compared with the subjective feelings of 43 cyclists via questionnaires. A strong correlation (−0.94) was obtained between the objectively measured DCI values and the subjectively assessed evaluations. This makes the DCI approach transferable to any other environment. This method has been applied to an entire road network within the historical center of the city of Olomouc (Czech Republic). It can further be used by bicycle track administrators to monitor surface quality, by planners to obtain relevant surface pavement values, and by individual cyclists for optimal route choice.

1. Introduction

Planning, construction and management of bicycle facilities are demanding and expensive processes. To ensure that cyclists will make use of such facilities, reliable data are needed. Cyclist's route choice is often surveyed (e.g., Hunt and Abraham, 2007; Kang and Fricker, 2013) and it is generally accepted that cycling comfort consists of several factors: environmental, mechanical and biomechanical factors, and physiological factors (Ayachi et al., 2015). Environmental factors (e.g., traffic conditions, path width, road geometry and surrounding conditions) significantly influence cyclists' evaluations of the comfort of bicycle lanes and shared roads (Li et al., 2012).

Bicycle tracks and roads designated for cyclists should also be safe and undemanding. Cyclists omit long ascending tracks, particularly when commuting to work (Milakis and Athanasopoulos, 2014). Every day bicycle commuters usually use the fastest routes, because they are experienced riders (Menghini et al., 2010). Certain road surfaces may be difficult to ride on a bicycle and along with other factors may discourage people from using their bicycles. Comfortable cycling requires smooth rolling at the lowest possible energy input (Hölzel et al., 2012). The surface pavement type (e.g., Walker, 2002) is often included (along with other factors, such as traffic volumes and road width) in the assessment of optimal routes for cyclists, which is part of bicycle network analyses (e.g., Rybarczyk and Wu, 2010).

* Corresponding author.

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Optimal cycling routes are usually planned by the Bicycle Level of Service (BLOS) approach. An example of such a methodology is the approach of Landis et al. (1997) who used 5 levels of surface quality (very poor, poor, fair, good, and very good) for the surface pavement type. They made a valid point stating that the pavement condition is frequently dismissed by some practitioners as being insignificant. The response to real-time stimuli captured in their study does confirm that pavement condition plays an important role in cyclists' assessment of roadway environment. A common system of surface pavement quality evaluation is, however, subjective (e.g., Walker, 2002). Objective road quality for cyclists is usually not part of the indices used to predict bicyclists' perceptions of a specific roadway environment, e.g., the bicycle compatibility index (Harkey et al., 1998).

Older people, women and experienced cyclists, as demonstrated by Bergström and Magnussen (2003) or by Stinson and Bhat (2005), attach more importance to a smooth surface. A poor road surface is thus a discouraging factor which strongly affects the supply side in the bicycle transportation planning process. Actual pavement surface condition is thus one of the variables influencing the route choice of a cyclist (Landis et al., 1997).

Impacts of poor cycling track surfaces or road surfaces in general on the decision of a cyclist to use a particular route have not been widely studied thus far (Heinen et al., 2010; Joo et al., 2015). We could only presume that if cyclists would have a choice they would select the smoother routes. The study of Landis et al. (1997) is among the few works which explicitly states that surface quality is an important decision factor for cyclists when choosing a cycling route. The vibration of a bicycle is often a prominent consequence of poor cycling track quality. Cyclists perceive bicycle vibrations negatively (Landis et al., 1997; Torbic et al., 2003) and therefore the direct measurement of vibration should be applied to the cycling network. This is particularly needed if such a network consists of sections of various surface pavements and age.

1.1. Vibrations and cycling comfort

Cyclists perceive surface quality by way of bicycle vibrations which are among the important causes of discomfort (Thibauldt and Champoux, 2000; Giubilato and Petrone, 2012). As vibration increases, comfort decreases (Torbic et al., 2003). The main reason for vibrations is an uneven road pavement (Olieman et al., 2012). Hölzel et al. (2012) studied the effects of four different road surfaces (asphalt, concrete slabs, cobblestones, self-binding gravel) on vertical acceleration, including less used and worn surfaces. They conclude that the most comfortable were asphalt surfaces and the least worn concrete slabs. They also found that cycling comfort decreases with higher velocities. Giubilato and Petrone (2012) studied the response of various wheel models to surface roughness. Their results indicate that the ranking between comfort properties of different wheels varies with the road surface roughness and the cruising speed considered.

Although bicycle designers are attempting to improve cycling comfort through various technical innovations (e.g., Vanwallenghem et al., 2012), an objective mapping of vibrations along cycling tracks and roads used by cyclists is still needed in any efforts to achieve higher quality in the cycling network or to localize problematic places.

Inertial sensors (accelerometers) are deemed ideal candidates to serve as pavement sensors for wide-area instrumentation (Levenberg, 2014). Joo and Oh (2013) used GPS and an accelerometer mounted onto a bicycle to derive Bicycle Monitoring Index (BMI). They combined data about vibrations and speed. They computed the probability of the suitability of a road segment for cycling. Their BMI has two aspects: mobility and safety. It is bicycle speed which limits the suitability of the road segment from the mobility point of view. If it is below 5 km/h, then the road segment is not suitable. The safety is then related to the acceleration level, which is approximated from Weibull distribution. The results presented by Joo and Oh (2013) are single numbers for the entire road segments, but without identification of places with local extremes.

Bicycles equipped with an accelerometer are often used for cycling track vibration mapping. Mohanty et al. (2014) present a review of current Instrumented Probe Bicycle (IPB) technology and research. IPBs are common bicycles equipped by several technologies which measure both bicycle position and acceleration (e.g., Joo and Oh, 2013). The sensors used often include, for example, a potentiometer to measure hand-brake depression (Lee et al., 2014), a lateral distance sensor (Yamanaka et al., 2013), a laser pointer (Angel-Domenech et al., 2014) or a camera (Dozza et al., 2013; Yamanaka et al., 2013). Measurement by means of such an IPB provides an abundance of data about cycling tracks, but it can be complicated to reproduce the results by other researchers.

1.2. Cycling comfort mapping in the Czech Republic

Strong support for cycling as an alternative to other modes of transportation was provided by the Czech government in the form of the National Cycling Strategy adopted in 2004. Since then various regional agencies have supported building cycling tracks and the construction of a supplementary cycling infrastructure. Approximately 39,000 km of marked cycling tracks are recorded by individual regions (Bíl et al., 2012). At present, the main effort is to standardize the entire network data, because they are administered with varying systems of data recording.

A new method for cycling-track mapping (Bíl et al., 2012) has been applied to approximately 15,000 km of the Czech cycling trails. Data is collected directly in the field riding a bicycle. One parameter describes the type of surface pavement (e.g., asphalt, cobblestones). Another parameter is the subjective estimate of the bicycle type which is suitable for the road section (e.g., mountain bike, touring bicycle or a racing/regular bicycle). Problems which have been documented in connection with this mapping lie in the fact that the same type of surface may be of varying quality or age. The mappers can also insert a point if they identify a dangerous place. There is still the need, however, for an objective (quantitative) way of cycling track mapping. The proposed method should fill this gap.

This paper contributes to current knowledge by adding a robust and objective vibration measurement in the form of *dynamic comfort index*. This value shall then be used among other factors in general BLOS models selecting suitable cycling routes. The entire setting of the devices during measurements is lucid and therefore effortlessly transferable in contrast to present-day probe bicycles which are rather complicated to reproduce.

2. Data and methods

2.1. Data

The method of objective dynamic comfort mapping was applied to the historical center of the city of Olomouc, Czech Republic, which has a road network with varying types of surface pavements. The base data consist of an urban road network and cycling trails. Examples of cycling-tracks pavements where the method was applied are shown in supplementary files.

We simultaneously collected data on cyclist positions and bicycle vibrations. The position data were obtained with a Garmin Oregon 550t GPS device. Data collection scheme was set as every single second recording (1 Hz). We used one of the most common types of GPS devices to capture the movement of the bicycle. The GPS device was mounted on the handlebars to secure the best possible GPS signal reception.

The vibration data were measured by MSR145s (an accelerometer) device with a frequency of 20 Hz, i.e. 20 records per second (Fig. 1). The accelerometer was firmly attached with adhesive tape onto the front fork of the bicycle. Only the vertical position of this device on the bicycle had to be secured to gain reliable data (see supplementary file). The shock absorber, when using a mountain bicycle, on the respective fork was deactivated. This fact is important because vibrations of a wheel with an activated shock absorber are significantly higher than those on a handlebar (Olieman et al., 2012).

2.2. Methods

We took advantage of the fact that both devices (accelerometer and GPS device) work on the basis of precise time measurement. The position of the bicycle was therefore directly linked by formula (1) with information on the vertical acceleration for the respective point along the cycling track.

The acceleration was measured with a high frequency (20 Hz) and influenced by measurement noise. The measurement noise follows, in our case, the normal distribution with a zero mean and standard deviation equal to 0.15 (this number was provided by the manufacturer).

2.2.1. Dynamic comfort index

We suggest the dynamic comfort index (DCI) inspired by Giubilato and Petrone (2012) to capture the information received from the accelerometer and to objectively represent the bicycle vibrations. The index is calculated per second from the measured values of acceleration $a_i \geqslant 1, i = 1, \ldots, n$, according to the following formula:

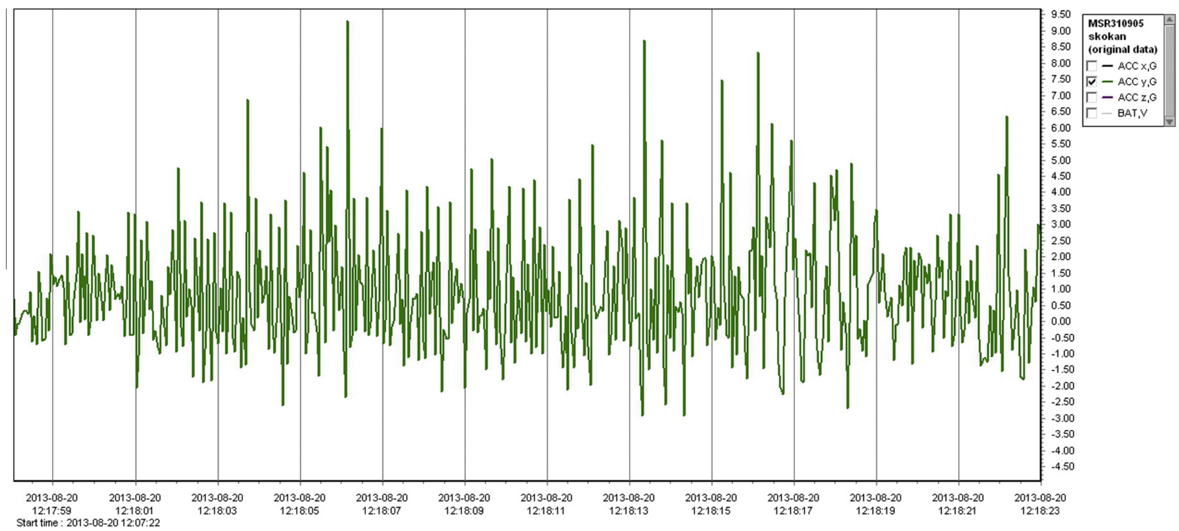

Fig. 1. An example of the raw data from the accelerometer segmented by time stamps. Data on vertical axis show acceleration.

$$DCI = \left(\sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i^2}\right)^{-1} \quad (1)$$

where n is the number of greater-than-one measurements during a single second. The DCI ranges between zero and one. It can be viewed as the inverse value of the energy contained in the signal of acceleration greater than the acceleration of gravity. We linked every GPS position with the corresponding single number calculated according to formula (1). The flowchart of DCI generation is shown in Fig. 2.

The DCI is indirectly related to the power of acceleration (vibrations). High DCI values therefore identify the more comfortable roads with less vibration. Roads with large vibrations are represented by low DCI values. The DCI performance is better than the simple use of the standard deviation, because the influence of the measurement error is lower in the sense of the relative error (see Fig. 3).

Test riders rode their bicycles from the beginnings of the cycling tracks to the ends at a constant speed of 15 km/h. The places where two neighboring segments met, e.g., curbs, were not mapped, because they could distort the results of the respective test segments. In the case of real mapping, these curbs and other irregularities where segments met should be mapped, to locate the points of significant shocks for the cyclist.

A direct link of DCI to the GPS position via time stamps allows for the precise Geolocation. With such geo -referenced data it is possible to visualize the DCI on a map. Quantum GIS 2.0 Dufour (Quantum GIS, 2013) was used to produce maps. Supplementary KML files were prepared in order to localize places mapped inside the city of Olomouc (see supplementary data).

2.2.2. DCI sensitivity to surface pavement type and bicycle speed

The extent to which the DCI values are dependent on the cyclist's speed was tested. Three 100 m long sections on smooth asphalt, worn asphalt and a cobblestone surface were selected. A decrease in the DCI values and the overall DCI range with increasing speed was found. It is natural that if cyclists ride slower, they are exposed to less vibration for the same roughness level. It is also difficult to maintain a steady pace primarily at higher speeds (Fig. 4). We therefore decided to maintain the speed 15 km/h as the standard pace for the vibration measurement. Measurements at lower speeds are not safe because the bicycle is less stable (e.g., Joo and Oh, 2013), whereas at higher speeds the DCI dispersion rises (see Fig. 5) and cycling within a town is also dangerous.

2.2.3. DCI values and subjective comfort evaluation by cyclists

We selected eleven sections (see Table 1) with various surface pavements and state of deterioration to compare the DCI performance. These segments were mapped and the DCI was computed for the entire length of the segment. 43 volunteers then rode their bikes on these segments. They were experienced (39) and occasional (4) cyclists; 9 women and 34 men; their ages varied between 18 and 68. They rode 5 racing bicycles, 20 touring and 18 mountain bicycles.

2.2.4. DCI sensitivity to bicycle type

We used three different types of bicycles: a racing bicycle, touring and mountain bicycle (see supplementary files). A test rider rode all three types of bicycles across the selected eleven sections in the same direction. The purpose of this testing was an investigation to which extent DCI is dependent on the bicycle type.

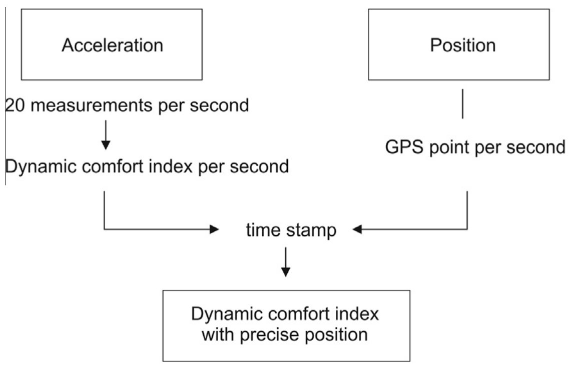

Fig. 2. A procedure for locating the DCI within a coordinate system.

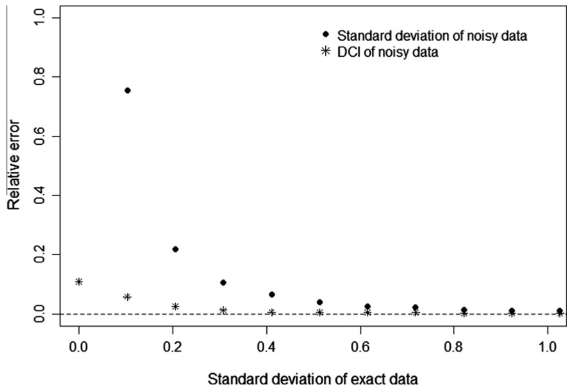

Fig. 3. A comparison of the relative error of standard deviation and DCI.

3. Results

3.1. The influence of DCI sensitivity on measurement noise

We used two accelerometers of the same type to test the influence of the measurement noise on the computation of DCI. The two-sample Kolmogorov–Smirnov test was applied to compare DCI distributions from two different accelerometers. Regarding all eleven pavement segments, it was determined that the DCI distributions do not significantly vary (e.g. see Fig. 5).

3.2. DCI sensitivity to bicycle type

We used the DCIs of mountain bicycle as a reference group for comparison with DCIs obtained from the other two bicycles. We applied the two-sample Kolmogorov–Smirnov test to compare DCI distributions. The results indicated that the DCI distribution within all eleven test sections was not significantly different (e.g. see Fig. 6).

3.3. DCI values and subjective comfort evaluation by cyclists

A close relationship was seen between the objective DCI and the subjective feelings reported by 43 users (Fig. 7). The volunteers answered the statement "*The ride on the bicycle on the given surface was pleasant*". They had six options to answer: strongly agree, agree, tend to agree, tend to disagree, disagree, and strongly disagree. A significant relation between the subjective (people) and objective (accelerometer) point of view was found. The correlation coefficient between the median of DCI on the entire road and the median of track evaluation by respondents was -0.94. The linear dependency is described by the following equation:

$$y = 8.2196 - 8.3166x \tag{2}$$

The DCI can therefore be easily interpreted as the level of vibrations experienced by a user.

3.4. DCI application to actual road pavements

We applied our method to eleven test sections (Fig. 8). The black circles indicate single values for every second spent on the respective cycling track (section ID on the horizontal line). The horizontal lines indicate median values for the entire set of individual measurements. The varying numbers of dots reflect the various lengths of the segments.

The DCI and its graphic representation (see Fig. 8) can help road administrators determine whether the given segment of road or of cycling track has a homogenous and smooth surface or not. The worst surface pavement was registered at section ID 3 and 9 (Fig. 8); the best surface pavement was registered at section ID 11. The outliers on segment no 5 indicate problematic places, e.g., holes, within a generally high quality surface.

3.5. DCI visualization

The map of the measured segments can provide, along with Fig. 8, a complete view of the cycling track quality and can also help locate the problematic spots. The DCI method was applied to the historical center road network of the city of Olomouc (see the supplementary KML file). The KML file provides a visualization of the individual places of DCI values with Google Earth. One can easily locate the places where it is rather difficult to ride a bicycle. The dark green color represents the

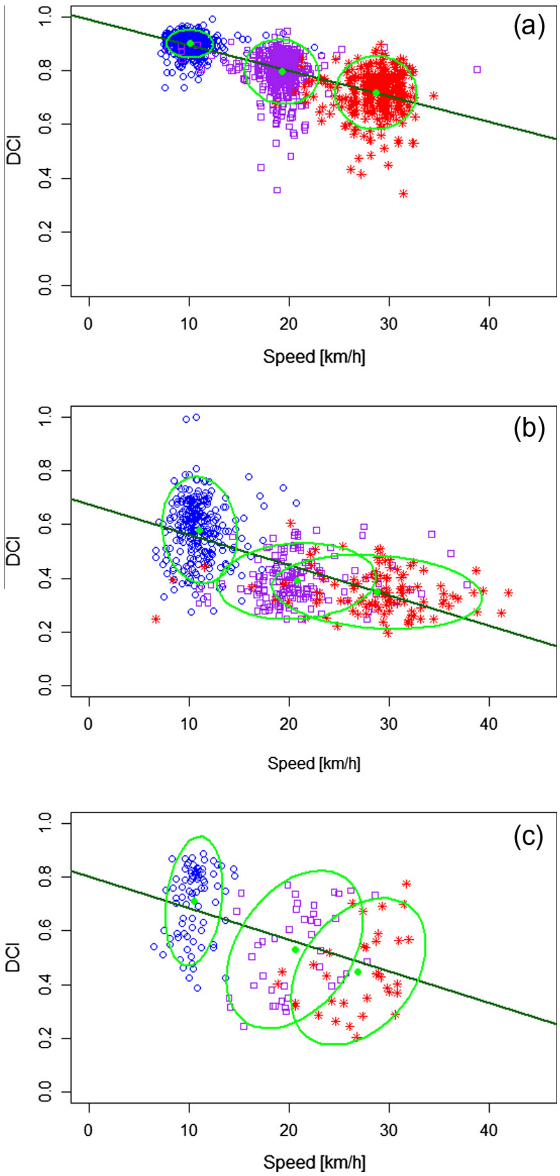

Fig. 4. The relationship between the objectively measured DCI and speed on (a) a smooth asphalt surface, (b) a cobblestone surface and (c) a worn asphalt surface. The symbols (circles, squares and asterisks) correspond to the prescribed speed of the bicycle (10, 20 and 30 km/h). The dispersion of points varies because it was not easy to maintain the speed, particularly if the speed was higher. The ellipses show 95% confidence areas.

smoothest pavement (usually roads in parks around the very center) and the red color represents places with the most problematic areas. They usually stand for old and uneven historical cobblestone pavements and damaged parts of roads. The point number, section ID and CI value are depicted after a click on a point on the map. Section ID corresponds to these in Table 1, section ID = 0 stands for other roads within the inner city.

4. Discussion and conclusions

The poor quality of cycling tracks and generally on-road or off-road cycling facilities may discourage cyclists from using them. There is therefore a need for a simple, transferable and objective approach to bicycle vibration mapping, because vibration strongly affects overall cycling comfort (Landis et al., 1997).

We presented an approach of simple vibration data capturing and a newly derived dynamic comfort index (DCI). Two forms of the DCI can be used in practice: the first one is an *aggregated* value linked to the entire cycling trail segments. This standard approach when a single number represents the entire segment is useful, but only in certain situations when

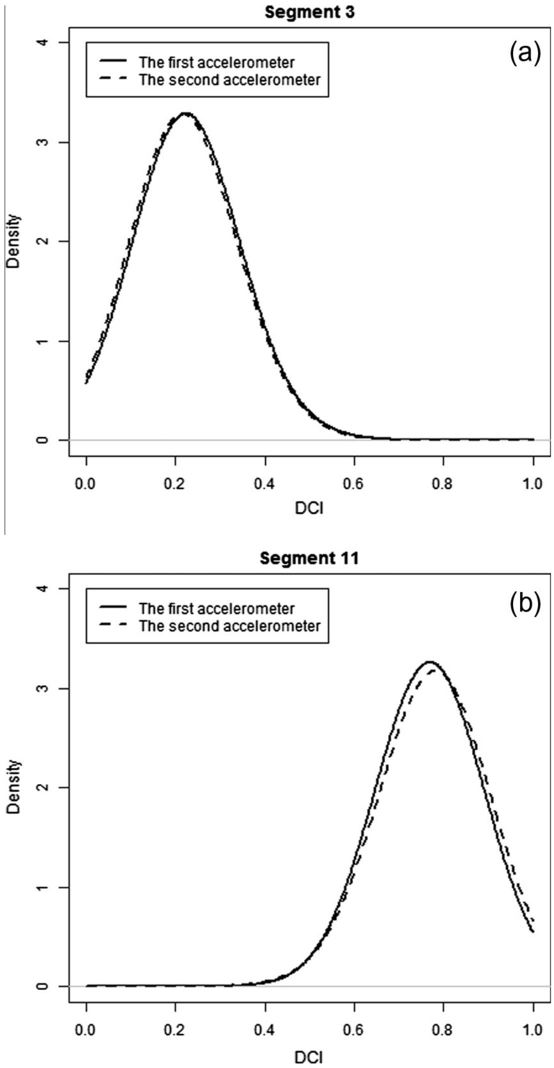

Fig. 5. A comparison of probability density functions of DCI from two different accelerometers on two selected segments.

Table 1
Summary of dynamic comfort index values depicted in Fig. 8.

Section ID	Length (m)	Surface type	DCI values				
			Minimum value	Mean value	Median value	Maximum value	Standard deviation
1	208	Old small granite cobblestones	0.2454	0.3861	0.3753	0.5941	0.0809
2	371	New cobblestones	0.4604	0.6922	0.7037	0.9206	0.0892
3	333	Old large granite cobblestones	0.2015	0.3258	0.3203	0.4994	0.0655
4	133	Worn asphalt	0.6057	0.7332	0.7441	0.8442	0.0634
5	466	Uneven asphalt	0.3868	0.7945	0.8172	0.9026	0.0911
6	212	Interlocking concrete pavement	0.5289	0.7108	0.7127	0.8119	0.0645
7	185	Uneven interlocking concrete pavement	0.3172	0.6043	0.6152	0.7880	0.0869
8	85	Unpaved path	0.4496	0.6452	0.6800	0.8131	0.0989
9	170	Old large granite cobblestones	0.2083	0.3125	0.3016	0.4261	0.0611
10	448	Old small granite cobblestones	0.2854	0.4631	0.4536	0.6677	0.0818
11	626	Asphalt	0.6928	0.8132	0.8192	0.9100	0.0544

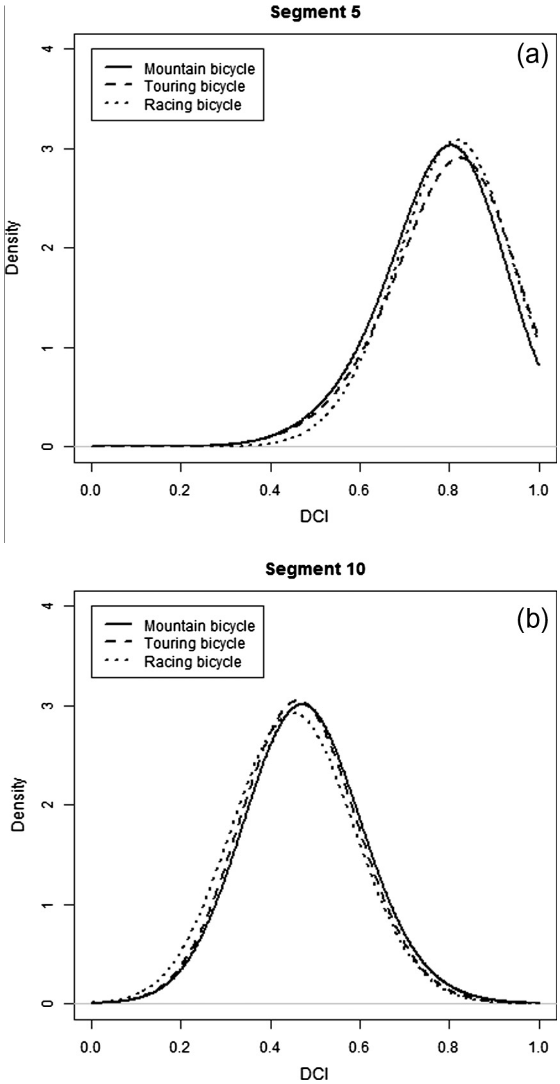

Fig. 6. A comparison of probability density functions of DCI on two selected segments.

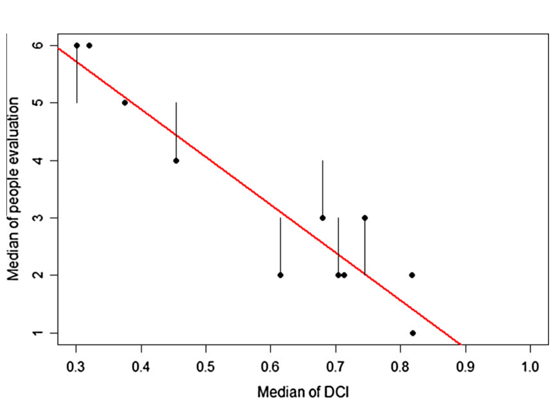

Fig. 7. Relationship between the subjective road quality evaluations carried out by 43 users and the objective measurement (dynamic comfort Index). The thick line is given by formula (2). The thin lines depict 95% confident intervals of medians of evaluation.

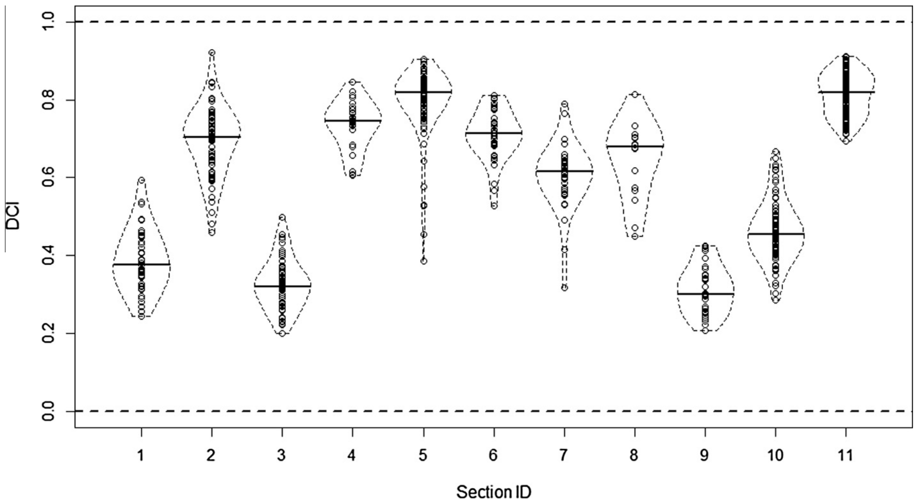

Fig. 8. Dynamic comfort index for all the measured roads and cycling tracks in the city of Olomouc.

the entire section has the same level of surface quality. A single number cannot represent the entire segment properly, if places with considerably different surface qualities within such a segment exist (e.g., settled places; holes). This is an example of section ID 5 at Fig. 8. It is also clear that a surface of the same type, e.g., cobblestone, may be of varying qualities along the entire segment. The second form of the DCI is a spot measure which also allows for measuring the *local extreme* value which identifies potentially hazardous locations even within a high-quality (e.g., asphalt) pavement.

The use of the suggested system of GPS and accelerometer devices is advantageous when comparing it with the common system of cycling track mapping as used today. It should save time and money because it is effective. It also allows for GIS and statistical processing, because the result is in the form of a continuous variable and not only a (subjective) categorical variable. Mappers can ride their bicycles without a need to stop when they encounter a settled place on a road.

Even more important advantage in using this approach and its numeric formulation in a DCI form is that it is objective and therefore does not rely on individuals and devices. Mappers will obtain the same results even when riding various bicycles. The objective value of the DCI is also advantageous, because it allows for a mutual comparison among numerous cycling trail segments. An objective network-wide evaluation among cycling comfort is therefore possible.

This study is in certain aspects similar to previous works where other authors also used their bicycles to obtain related comfort indices. The principal difference, which makes our approach widely applicable and easily transferable, is the use of the most common devices to gather data. Both GPS and the accelerometer devices can easily be acquired anywhere around the world. We have also demonstrated that the relative value of DCI is not dependent on the bicycle type. Sophisticated probe bicycles cannot of course be obtained and calibrated by anyone. IPB approaches are still useful particularly when studying the attitudes and perception of a limited number of people, but are not easily replicable by those who do not have the same equipment.

4.1. Potential users

Not only bicycle facility planners and road administrators will benefit from this objective method. Leisure cyclists can make use of the information about vibrations on planned routes. Numerous leisure time cycling activities are performed outdoors in mountainous regions. Young adults as well as families with children use cycling mountain and forest trails. Satisfaction with such a cycling trip can easily be disturbed by the quality of the cycling trail surface. They can be, especially in forests, uneven and rough. These users would in all probability welcome information on dynamic comfort provided in advance. Adventurous cyclists can, on the other hand, seek out tracks with maximum roughness. They are, in contrast to commuters and families, usually looking for uneven and undulating terrains when riding their mountain bikes (Pickering et al., 2010). This group could also be interested in such information in order to select the right track. Another potential use of the DCI is also in cycling maps and web map applications. If there is a routing system in such applications, the cycling trail data enriched by the DCI can be used for optimal path searching.

4.2. Limitations of this study and future research directions

Cycling tracks with significant steepness may indicate different DCI when riding an up- or downslope. The reason is the different bicycle speed. To obtain relevant data on actual DCI the mapper should ride 15 km/h, because vibrations depend on the bicycle speed (Fig. 5). Research focused on the relation between DCI and bicycle speed will therefore be useful.

We tested DCI performance on three different bicycles and eleven road sections. We argue that the suggested simple and robust method of data capturing can be applied worldwide, in contrast to rather complicated IPB technology. It would be desirable to continue to test this method and compute DCI for various bicycle–pavement combinations. We offer DCI computation from the delivered data for all interested persons.

The future direction of research is to a large extent strongly dependent on current day technology. Higuera de Frutos and Castro (2014) presented an interesting approach to road inventories by using smartphones. The only limitation to this approach is the need for external energy sources. This is not an issue inside a car, but on a bicycle it is still limiting. The existence and general accessibility of robust smartphones with extended battery endurance would allow for other improvements in this method.

This study differs from the previously published works as it presents a simple and robust setting for bicycle vibration measurement which is easily transferable, because it uses widely accessible devices. Furthermore, the bicycle facility mapping can be carried out from various bicycles equipped with standard devices to obtain widely comparable data. Dynamic comfort index (DCI), as an objective representation of cycling vibration, is also less sensitive than standard deviations to errors. DCI also allows the user to localize places within the road segments with problematic surface quality. This work is finally not a mere theoretical study but has already been applied to the local municipality of the historical center of the city of Olomouc and can be used anywhere to obtain a comfort map for cyclists.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trc.2015.05.007. These data include Google maps of the most important areas described in this article.

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