

# ANALYSING THE VIBRATION OF BICYCLES ON VARIOUS ROAD SURFACES IN THE CITY OF ŽILINA

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## Abstract

Over recent years, cycling has emerged as a particularly desirable mode of transport in Europe. Many local authorities, together with cycling lobbyist and advocating groups strive to get cycling to an accepted level of urban mobility. Certain movements have already introduced the citizens' science approach aimed at improving the local conditions for cyclists with crowd-sourced data collection. With this in mind, this paper presents an entry-level analysis of vibration from various surfaces which might affect the comfort of cyclists in the city of Žilina. The emphasis is placed on the analysis of the road surface with a smartphone application and a so-called instrumental or a probe bicycle. The results of testing are presented in the context of the problematic issues that occur in the infrastructure. The results are aimed at drawing attention to the fact that not all infrastructure is properly built, designed or maintained. There is a relationship between properly planned and built cycling infrastructure and the cycling traffic. An Android smartphone with the Phyphox application was used in the analysis as an example of citizen's science.

**Keywords:** vibrations; vehicle safety; vibrating comfort, cycling

## 1. Introduction

Every road user requires the appropriate quality of road surface in order to have a comfortable ride. This especially applies to particularly vulnerable road users such as cyclists and pedestrians belong, who consider the road quality as a significant factor in the process of journey planning in the geographical or spatial context [26].

The validation of the quality of bicycle network [1] is a common requirement together with validation of other transport networks. The cycling networks are mostly underestimated in the sense of proper planning in comparison with other transport networks. In theory, the car users and cyclists should have equal rights; however, the level of quality of the constructed infrastructure proved a different result. If the cycling infrastructure is not planned and designed properly, the cyclists will be deterred from using it; even if it is built [42]. Planning proper cycling infrastructure that will meet the various quality criteria is seen as one of the aspects of successful usage of cycling infrastructure [12]. Therefore, we can see the difference between the plan and reality of the final construction of cycling

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infrastructure, which faces problematic level of usage [35]. Therefore, we can find cycling networks consisting of low-quality cycle tracks or roads that would fail the consideration for the prospects of being used from the perspective of their attractiveness. The quality of transport infrastructure can be analysed from various perspectives. The comfort of the use of the network can be evaluated with technical tools, such as sensors and also through obtaining feedback from users. This is mostly possible through the application of professional or so-called expert tools. The current progress of information technology enables the use of broadly available technology that is present in almost every household - the smartphone. The smartphone has become a new technological gadget which not only provides communication but also offers a lot of functions related to entertainment, work and also to research. The available platforms, such as Android and iOS also offer various opportunities with software which is mostly free. This also applies to the field of science and research. Modern smartphone is equipped with multiple technological features - sensors which have the potential to turn the smartphone into an interesting research tool or even a scientific lab.

Another aspect of network evaluation is the public engagement in the planning process, and it represents the emerging need from various citizens' movements, or advocacy groups gain the relevant evidence in order to support the importance of the improvement of poor results. This is possible with citizens' science approach. So-called citizen science [4] is nowadays an exciting platform for active citizens who intend to improve various issues [16, 36].

## **2. Analysing the ride comfort of the cyclists.**

The subject of cycling ride comfort has been researched in many studies [ 9, 25, 49]. In general, we can classify the analysis of cycling comfort from various perspectives (e.g., measuring the vibration, emotion, etc.) with information technology, the second example contains an analysis from the cyclists' perspective, reflecting their opinions and feelings or evaluating the ride during cycling [10, 24].

Measuring the comfort with technology and techniques can provide information about how the surrounding environment affects the means of transport - in this case, the bicycle. Vibration is not a desirable feature for either cyclists or car users [20]; therefore, vibration is perceived mostly as discomfort during the ride. Therefore, probably most cyclists intend to minimise this discomfort as much as possible. In general, there are many factors that affect cycling ride (see Figure 1). The comfort of the ride can be affected by the quality of transport infrastructure, which is the primary focus of this study but there are also other factors or parameters, such as the personality of the rider. In this case, it is a combination of mental and behavioural features and preferences. Other factors include weather and other external factors, such as other transport modes that might affect the perceived comfort of the ride of cyclists.

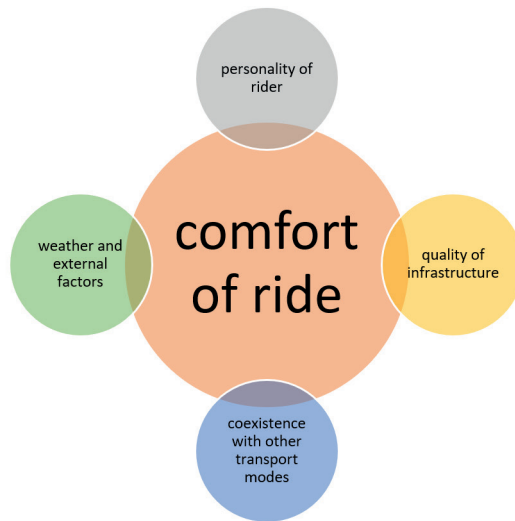


Fig. 1. The comfort of the ride and the main groups of factors affecting it

The worst consequences of vibrations are those that can affect health, e.g., the back or other parts of the body. Of course, for some cyclists who participate in mountain biking or downhill riding, the vibrations are expected, and they are part of the ride as such. It is also possible to analyse the disturbances of the ride caused by various infrastructure facilities [8].

Another aspect that needs to be considered is the type of bicycle. In general, bicycles are mostly designed for urban environment (e.g. city and urban bicycles) and are not equipped with the suspension to reduce the vibration. Various mountain bikes (MTB) are equipped with full or partial suspension. The bicycle suspension aims to protect the cyclist and cushion him or her from the roughness of the terrain. There are also other bicycle types called cross bicycles, bicycles designed for athletes or racers, the racing bicycles and also different types such as cargo bicycles, folding bicycles, etc. We should not also forget to mention bicycles with electric power.

Most types of urban or city bicycles are not equipped with a suspension system, with the possible exception of the saddle. However, the cyclists-commuters expect a smooth ride without vibrations. This is also linked to the road quality evaluation which needs to be measured [5].

For the purposes of this paper, potential methods for analysing the comfort of cycling have been investigated.

## 2.1 Analysing the roughness of the road surface

In the evolution of designing or planning the transport infrastructure, there was still a tendency to measure or analyse the road quality from various aspects [30]. The inequality of roads contributes to the fact that the road users are not satisfied. This fact presents a problem if the financing of transport infrastructure is funded from public sources.

The roughness of any road can be observed as vibration. This is linked to another consequence, for instance, more energy is needed to overcome disturbances of this type [19]. In the past, there were various methodologies which were introduced [49]. They are represented by indexes or methods analysing the road surface quality [2] such as International Roughness Index (IRI) [55], Present Serviceability Rating (PSR), Root Mean Square Vertical Acceleration (RMSVA), Mean Panel Rating (MPR), Ride Number (RN), Slope Variance (SV), and Profile Index (PI) [15, 45, 47] or rolling resistance measurement [24].

Probably one of the most used ones is International Roughness Index (IRI) which focuses on the measurement of longitudinal road profiles. It is based on the single profile measured in one of the wheel path of a road surface. It also has another variation as Mean Ride Index (MRI) and Half Car Ride Index (HRI)[FHWAY]. The HRI averages the two profiles (left and right wheel paths) [24].

The roughness of the road surface is usually measured with professional tools, mainly with cars equipped with various sensors, lasers, etc. Such technology is not available on a daily basis, and due to its high cost, it is mainly used by professionals or road authorities. Another approach is Response-Type Road Roughness Measuring Systems (RTRRMS) [37] which measures the vertical movements of the rear axle of a vehicle or the axle of a trailer relative to the vehicle frame. The modern approach is the scanning of the surface with 3D Lidar systems [24] and making a 3D model of the road surface with indications of potentially problematic areas. This type of technology and tools are expensive, therefore, their potential use on a small scale analysis is very limited. The professional expert testing is mostly performed with certified professional equipment which also provides more precise results. However, this is limited only to vehicles where the technology is installed, mostly applied for car vehicles. However, this approach reduces the possibility to test everywhere because of the availability of the testing vehicle and considering the financial aspects (cost of technology including the car, software, hardware, operation cost, etc.). These kinds of approaches are not in favour of citizens' science [40].

## 3. Methodology

In the process of analysing the comfort of a cycle ride based on the reviewed methodology, various approaches have been considered [48]. Several approaches are described in Table 1. The study conducted by [11] introduced the dynamic comfort index which is derived from the accelerometer. The negative of such approach is the level of the instant measuring which means that the cyclists are not able to recognise the dynamic feature. The research performed by [22] has examined how pavement-tyre interface influences the cycling comfort in views from the pavement-tyre contact interface. It establishes a Dynamic

cycling comfort method, and it provides the recommendations for asphalt pavement design for bike lanes. Rolling resistance was measured in previous research [25]. On the other hand, the study by [10] focuses on the measuring of the bio-physical activity of cyclists. The measuring of the cyclists' anger scale was the primary results of the study [41].

In general, there are two main approaches. The first approach focuses on capturing data from various types of sensors and technical tools, such as accelerometers [41], GPS, video cameras or other sensors [42, 53]. The potential technologies and tools are described in [10]. This will help conduct the dynamic analysis of vehicle [14], in this case, a bicycle. The second approach employs subjective cyclists' evaluation mostly presented on the basis of questionnaire. The study [41] published the Cycling Anger Scale (CAS) and it confirmed the 12-item four-factor model of the CAS amongst a cohort of Australian cyclists.

**Tab. 1. The overview of measuring the bicycle comfort**

Study	Tool	Description	Bicycle type	Various road types
[25]	GPS; accelerometer	rolling resistance	racing	Yes
[11]	GPS; accelerometer	DCI- dynamic comfort index	MTB	Yes
[21]	GPS; accelerometer, Thermometer; 3D scanner	DCC- dynamic cycling comfort	urban	Yes
[56]	video camera	CCI-cycling comfort index	urban	Yes
[53]	GPS; accelerometer	IRI- International Roughness Index	urban	Yes
[10]	Bio/physical sensors	Body reactions	NA	No
[41]	survey	Cycling Anger Scale (CAS)	NA	NA

Primarily for these reasons, the measuring with the smartphone and instrumental bicycle was identified as the main component of the analysis. The idea is not new - there have been several trials with a bicycle representing the main instrument for ride comfort analysis. Some studies conducted the test with instrumental [38] or probe bicycles [52, 53, 56]. A probe bicycle is an interesting tool which can provide on-site information at low cost. Due to the availability of bicycles it is not a problem to conduct such kind test almost everywhere. There is also evidence of analysing of the road surface with smartphone. [28, 46]. During the research, various types of apps have been tested. For instance, the RoadLabPro [18] which makes sense for measuring with cars, but it is not ideal for simulating the cycling condition. One of the limited conditions or requirements for the appropriate analysis is the operational speed which is designed for cars.

And why smartphone as the analysing tool? At present, the market of smartphones also offers a wide scale of suitable smartphones [17] that allow the measurement of the basic dynamic or physical features based on the built-in sensors. A considerable advantage of smartphone is illustrated the fact that the penetration in the smartphone market reach is significant in most developed countries [47]. Such an approach is described in various studies [34, 37]. The use of a smartphone for such analysis can provide a basic level of analysis which corresponds to the analysis of a wide cycling group in comparison with analysis with

professional tools that are used mostly for road investigations. A review of the smartdata sensor for road surface inspection is presented in literature [46]. On the other side, there is smartphone software that allows the investigation of the road status by measuring basic features of the road surface. Of course, they are not as precise as the professional tool, but they provide a brief overview of the road vibration and its quality. The main disadvantage of such an approach is the fact that most software was developed for car-based measurement. The study conducted a trial also with certain features of such software freely available from Google Play [23] as RoadlabPro [44], Road Bounce, RoadBump, etc.

The analysis consisted of the following steps:

- choosing the testing site;
- hardware and software preparation;
- data collection;
- data analysis;
- problem description.

The measuring instruments consisted of both hardware and software components. The testing consisted of the hardware equipment represented by bicycles and smartphone and smartwatch.

Hardware:

- the urban e-bicycle without suspension;
- Motorola G5 Plus smartphone with Android 8.0;
- Amazfit Pace smartwatch served as an additional tool for measuring the GPS tracking and some physical features.

The probe or instrumental bicycle is shown in Figure 2. There is also a smartphone located and secured on the rear rack with indicating the x, y, z axes, where y axe represents the direction of ride, the z axe captured the vertical displacements.



Fig. 2. Instrumental bicycle and smartphone indicating the x, y, z axes of the accelerometer

#### Software:

- Phyphox version 1.1.5;
- Strava;
- Endomondo.

The software equipment represents a freely available application allowing to measure the vibration, therefore the Phyphox software was installed in the smartphone. This software was developed by RWTH Aachen University [39], which can be downloaded from Google Play. It allows a wide range of experiments based on smartphone sensors. The specifications of availability and sensors can be found in the database of submitted smartphones on the Phyphox website. The smartphone accelerometer was used with the aim to measure vibrations. The indication of x, y, z axes is shown in Figure 1. For GPS tracking, smartwatch applications and smartphones were used. For the purposes of a possible comparison of the obtained results with a smartphone, the accelerometer specifications are provided.

#### Accelerometer (type 1):

- Name: LSM6DS3 Accelerometer;
- Range: 78.4532 m/s<sup>2</sup>;
- Resolution: 0.0023956299 m/s<sup>2</sup>;
- Min delay: 5,000 µs;
- Max delay: 1,000,000 µs;
- Power: 0.9 mA;
- Vendor: STMicroelectronics;
- Version: 1.

#### Linear Acceleration (type 10):

- Name: Linear Acceleration -Wakeup Secondary;
- Range: 78.4532 m/s<sup>2</sup>;
- Resolution: 0.0023956299 m/s<sup>2</sup>;
- Min delay: 5,000 µs;
- Max delay: 200,000 µs;
- Power: 1.7999878 mA;
- Vendor: QTI;
- Version: 2.

The testing sites were chosen based on the criterion of cyclist movement, and they considered the planning these segments as part of prospective cycling network within the master transport plan of the city of Žilina.

In the analysis, the following types of road surface were analysed:

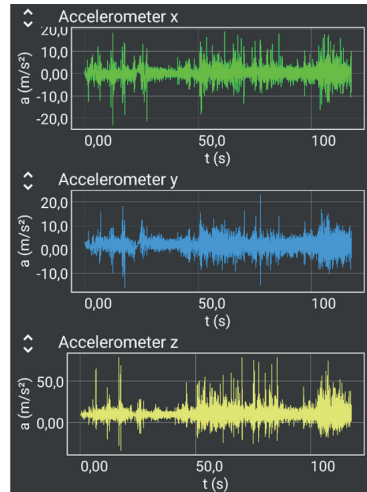
- cycletrack paving;
- unpaved natural trail;

- residential road with a smooth Surface;
- cracked residential road.

The first tested site was the natural trail with an unpaved surface. This trail is used by cyclists along the River Rajčianka and it constitutes a proposed corridor for a regional cyclistroute. The route condition is not suitable for urban bikes, and as is seen in Figure 3b, the vibrations have been higher than the ride on the asphalt surface during the whole ride test.



(a)



(b)

Fig. 3. The types of natural trail: (a) narrow natural trail, (b) measured vibration

The following cycling infrastructure analysed was a segregated cycletrack and a sidewalk (see Figures 4a and 4b). Although it is a segregated cycletrack with paving, the discomfort of vibration is caused mainly by the curbs that separated the entry to houses.



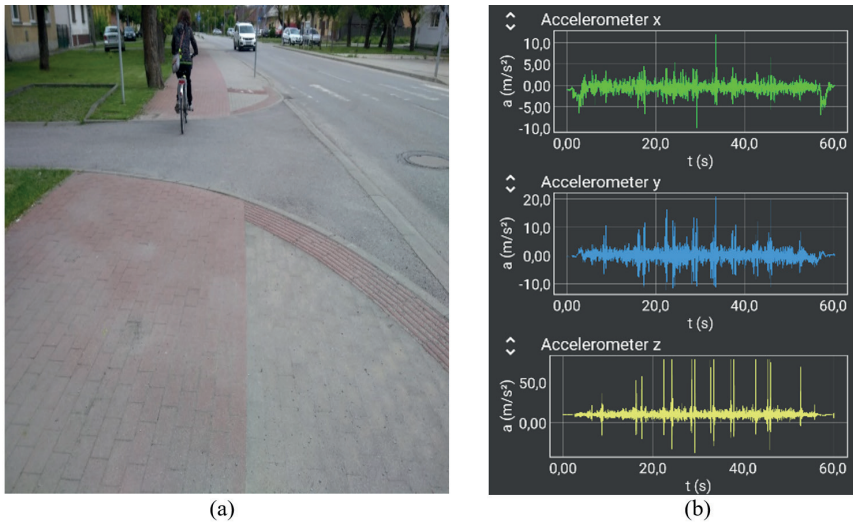


Fig. 4. Paved cycletrack and sidewalk: (a) cycletrack, (b) vibrations

This segment was also measured with a virtual accelerometer (without G) and the results are presented in Figure 5.

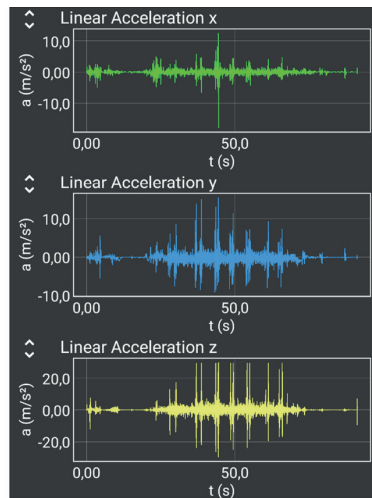


Fig. 5. Paved cycletrack measured with a virtual accelerometer

Another tested sites were two streets in the same residential area. Both streets are very close to each other, however, the quality of surfaces significantly differs, as can be seen in Figure 6.



Fig. 6. The residential streets with different road surface quality: (a) cracked asphalt, (b) smooth asphalt

The measured data are depicted in Figure 7. The vibrations on the cracked asphalt can be seen on the left and smooth ride on the right.

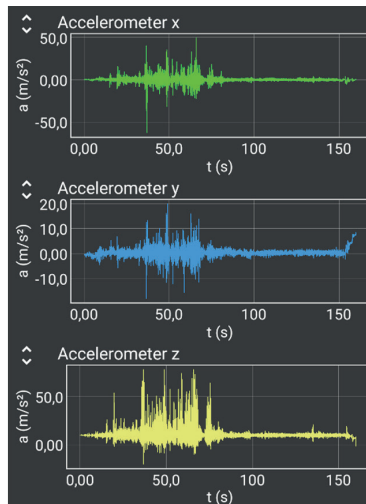


Fig. 7. The measured vibration during the ride on these streets

Vibrations were also measured on a brand new paved cycletrack with a high cycling traffic in the city of Žilina. The cycletrack is covered with asphalt and with small paved segments close to crossings (see Figure 8).



Fig. 8. A brand new paved cycletrack: (a) new surface, (b) segments with crossing and paving

The crossing to and from the cycletrack is the most vibrating part, see Figure 9.

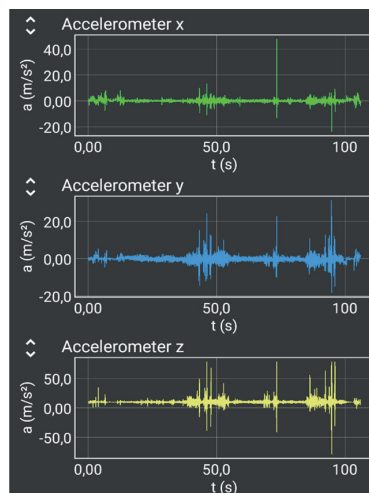
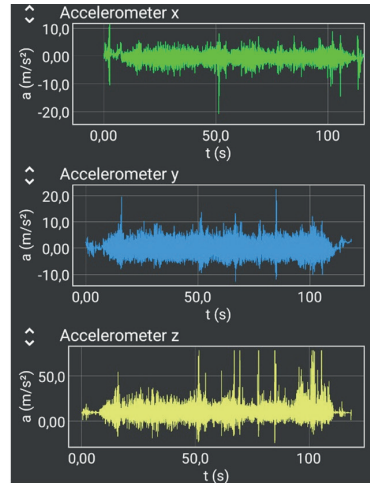


Fig. 9. Measured vibration on the Vysokoskolakov cycletrack

The following test site represents the bridge connection from the most populated city part Vlačince with a very poor surface, see Figure 10.



(a)



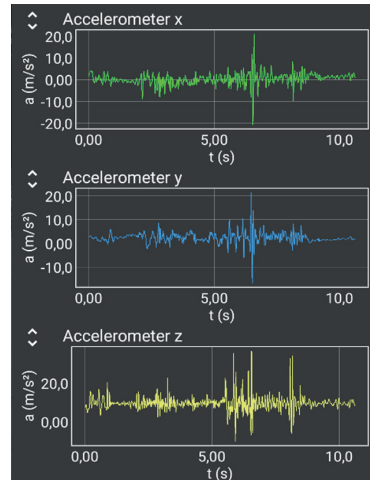
(b)

**Fig. 10. The bridge for pedestrians and cyclists: (a) the bridge, (b) measured vibrations**

The test also investigates the vibration of the bump, see Figure 11. It would be interesting to compare the results with cars as is presented in study [29].



(a)



(b)

**Fig. 11. The residential street with bump: (a) location, (b) measured vibrations**

There is also location where there is a plan for a new regional cyclerooute and it is used by cyclists to ride from the city to suburbs and to the countryside. This part of the segment has an unpaved natural surface with close locations of garages and sites of small gardening areas. The result of the measurement is shown in Figure 12.

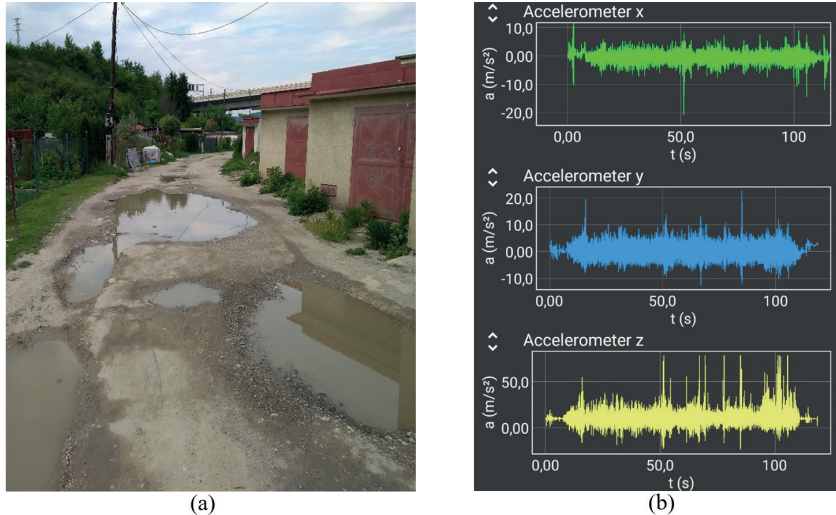


Fig. 12. The recreational area with garages: (a) location, (b) measured vibrations

Vibrations were also measured in the segment with a bridge and cars on the street connecting the city with the industry area (see Figure 13). In this segment, the high vibrations are caused mainly by passing through the railway track with a higher speed because the effect of the ride which is up and down.

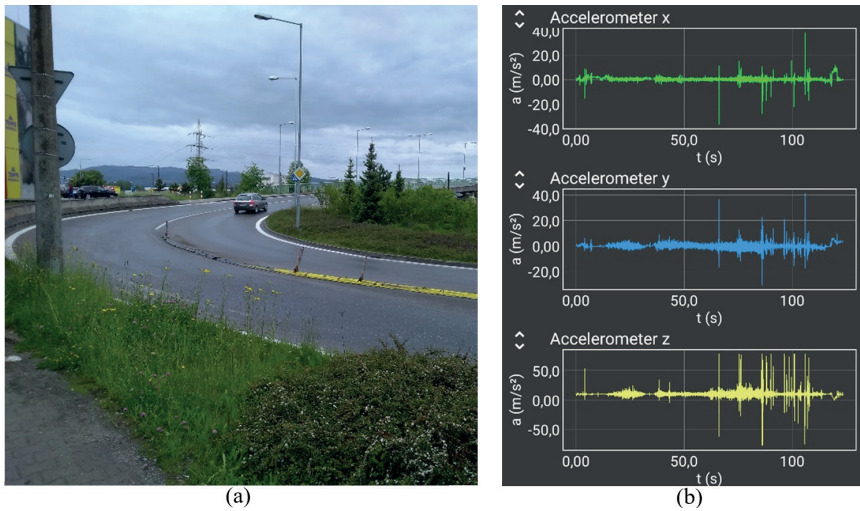


Fig. 13. The road over the bridge heading to industry area: (a) location, (b) measured vibrations

As for the comparison how the car is responding to vibrations, the test with a car in the short segment was performed. The test area covered the roundabout and a connection road. The result is depicted in Figure 14. The car's vibrations are lower than vibrations of an urban bicycle due to the suspension which is mounted in the car.

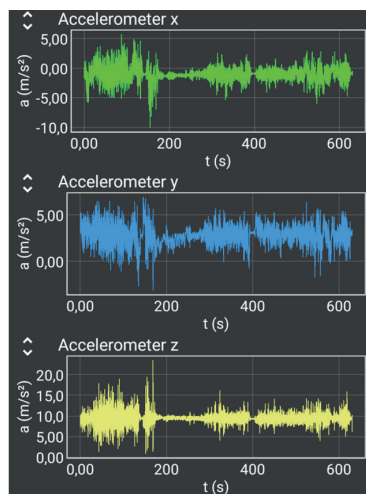


Fig. 14. The car segment vibrations

The results provided interesting outcomes. There is a clear evidence between vibrations affecting cyclists' comfort of ride and surface-type. This could be critical information for potential users in the decision making process whether to ride a bike or not.

Based on such the entry-level investigation and analysing the vibration data on various road types, it is possible to see the various level of road surface quality. The overall segments are depicted in Figure 15. The numbers represent the test sites numbering according to the figures presented in the paper.

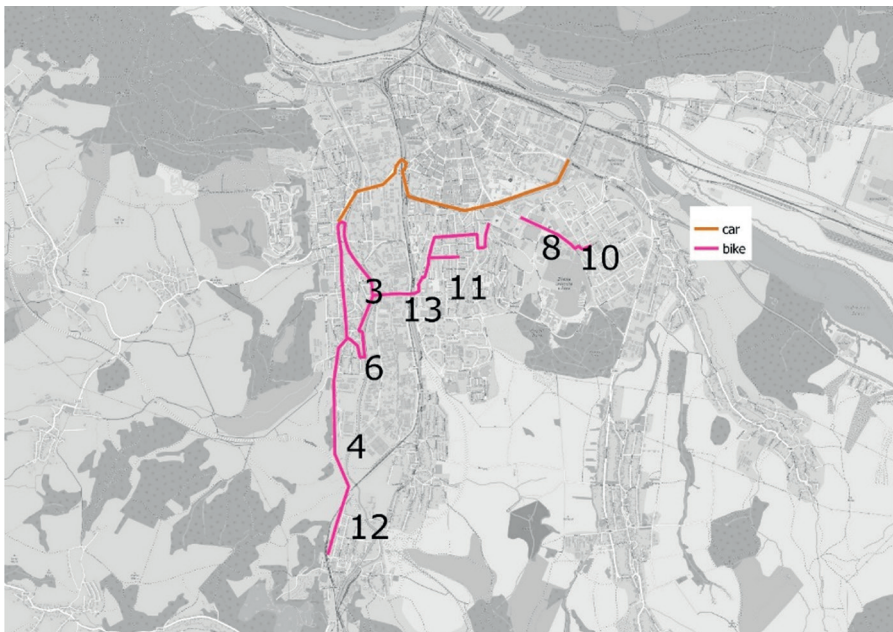


Fig. 15. Locations of the testing sites across the city of Žilina

Especially for cyclists riding on urban bicycles, the vibrations are presented in majority of segments with various surface types. There are also problematic segments on the brand new cycletrack with the discomfort of the ride. This is caused by crossing the streets, changing level from road to cycletrack or vice versa. We can also see that the potential planned cycle routes are currently only natural unpaved trails which will not attract people from cars to cycling.

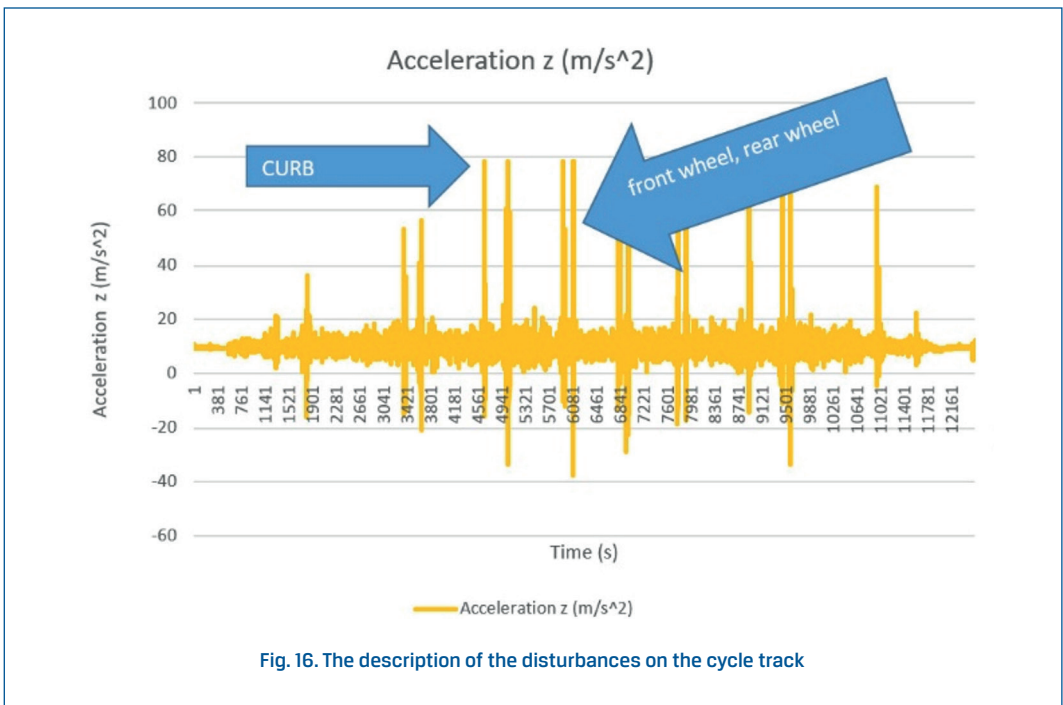
The most problematic areas causing the high level of vibrations are:

1. curbs;
2. bumps;
3. surface roughness of paved surface as cracked asphalt;

4. paving surface;
5. natural trail surfaces etc.;
6. mixing of old and new surface with insufficient quality of finished road works;
7. crossings etc.

In many cases, the roughness of the surface had extreme values which exceeded more than 15 mm, which, according to the IRI is considered a dangerous state. This is mainly in the residential areas where the quality of the surface is not so high and requires reconstruction.

Roughness of the road surface on the cycle track problematic - in these cases, a smooth segment of the surface is interrupted by large curbs (see Figure 16).



These results should be discussed with responsible authorities, mainly with city officials aiming to establish new standards as to how to plan or design cycling infrastructure.

## 4. Discussion and future research

The comfort of cyclist riding and linking to cycle infrastructure is related to the aspect of the designing, maintenance or future development of cycling infrastructure or general transport infrastructure. The output of this research contributes to enhancing cycling infrastructure with providing sufficient evidence for responsible authorities. The roughness



or vibration analysis can contribute to various other approaches one of which is referred to as the bike ability [10, 54]. The analysis of bicycle comfort should be incorporated into methodologies such as BLOS or BCI. There are two basic approaches which can make use of such data. The improvement of BLOS [9, 30, 49], where the bicycle infrastructure is examined similarly to vehicle Level of Service (LOS) and secondly, Bicycle Compatibility Index (BCI) should serve to the authorities and practitioners to plan and design cycling infrastructure together with other means of transport, mainly cars [36]. The harmonisation of BCI and BLOS have been published in various studies [27, 45]. The BCI methodology allows decision makers to evaluate existing transport infrastructure and determine possible improvements and requirements for new facilities [13].

Similarly, with the result of the study [21], the measurements provided the information about the current status of road surface for cyclists [43]. This should be a new requirement for a municipality for enhancing the level of road network maintenance also for cyclists and pedestrians. It is also possible to introduce the concept of bicycle level of service (BLOS) as summarised in literature [33] together with BCI [30]. Consequently, many factors affect bicycle traffic and usage [6, 32, 51]. The assessments for bicycle travel have been conducted and have been based on comfort, convenience and safety.

This study can be extended with additional measurements such as the impact on body health, as is mentioned in [7]. Another interesting aspect can be related to the automatization of the smartphone data processing in SMART city issue [31, 50]. This can lead to the future framework for analysing the cycling environment with smartphones equipped with various sensors enabling the capturing the data about the vibration, speed, environment, visual data or an instant evaluation of cyclist with voice recorder. The critical role of how to understand and present data lies in the usage of GIS [3]. Visualising the level of quality the urban road, including the cycling might provide helpful insights to decision-makers who systematically work on the improvement of cycling infrastructure.

The main limitations of the study are one type of bicycle and the output data in a raw format. Therefore, in the following stages of research, it will be possible to process such data and extend the methodology with various bicycle types and add the cyclists' evaluation of the infrastructure quality. The next research will be focused on the acceptable level of vibrations for cyclists.

Provided data are suitable for:

- verifying and analysing the current status of cycling infrastructure;
- providing data about the smoothness of the surface;
- proving the concept of crowd-sourced data for citizens science;
- recommendations concerning surfaces for cycling infrastructure;
- extending the analysis to other bicycle types or different modes such as pushchairs and wheelchairs;
- linking to Smart city and mobility issue;
- the creation of OPEN DATABASE with visualisation in GIS.

## 5. Conclusion

This paper presents a potential approach for smartphone-based analysis of road surface vibration. The study has analysed the relationship between vibration and various types of cycling infrastructure or general roads used by cyclists. The analysis has combined the data from an accelerometer with GPS data, and it is possible to extend it with feedback from users. The testing includes the measuring with instrumental bicycle and smartphone with freely available software allowing to collect data from the accelerometer. This entry-level data is suitable for further analysis with the potential to develop a new framework of evaluation of bicycle ride comfort on various surface types. There was a significant difference in vibration evidence of smooth pavement in comparison to natural or unpaved or cracked surfaces.

The usage of the smartphone as a research tool can be empowering for various citizen groups to engage.

Moreover, this type of data is valuable for citizens' engagement or citizens' science movement which can retrieve an important tool for pushing on the quality of cycling infrastructure.

The measured data can contribute to the open data database focusing on urban mobility evaluation. This issue is linked to the level of accomplishing the desired Bicycle master plan or condition for cyclists with reality.

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