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A review of state-of-the-art vibration analysis in assessing the comfort level of cycling surface quality

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Abstract

Bicycling is a mode of transport that is both environmentally friendly and provides numerous health benefits. The bicycle infrastructure should be comfortable and safe to attract more people to use bicycles. A poorly maintained bicycle route pavement creates vibration, which is undesirable for bicyclists because it creates discomfort during the trip. Over the years, bicycle vibration has been used to assess cyclists' comfort. This research presents a detailed overview of the methods that have utilized bicycle vibration to assess the comfort of bicyclists. Data extraction includes identifying the authors, year of publication, location, study design, assessment tool, and data source. Fourteen studies satisfied the inclusion criteria and are considered for analysis. The studies were conducted in various geographical locations, most in Europe. Both objective and mixed methods are used. Objective studies only depend on the sensor data, while mixed approaches also include cyclists' perceptions. The studies used multiple methods to assess the collected data, including Dynamic comfort index (DCI), bicycle comfort mapping, behavioral risk indicator, RMS (Root Mean Square), IRI (International Roughness Index), vibration and visual inspection, BEQI (Bicycle Environmental Quality Index), Cycling Comfort Index (CCI), Dynamic cycling comfort (DCC), surface condition rating-scale and rolling resistance. Studies are increasingly opting to use mobile applications to take advantage of smartphone sensors. Smart bicycle lights are also used as low-cost alternatives to the expensive instrumented probe bicycle.

Keywords: cycling comfort; bicycle vibration; bicycle surface pavement quality; sustainable mobility

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1. Introduction

To increase active transportation and establish an environmentally friendly urban transportation network, many cities worldwide are expanding bicycle infrastructure (Ahmed et al., 2024a; Ni et al., 2024). Cycling has advantages at both the societal and individual levels. At the societal level, increased bicycle use has long-lasting environmental advantages that support energy efficiency and create a pleasing atmosphere by reducing CO2 emissions, air pollutants, and noise pollution (Ahmed et al., 2024b). Bicycle promotion can reduce healthcare costs by decreasing the chance of diseases related to inactive lifestyles. Research shows that increased active mobility, i.e., walking and cycling in urban areas, could save approximately 17 billion pounds for the National Health Service UK (Jarrett et al., 2012) as the occurrence of diseases associated with physical inactivity will decrease.

Bicycling helps achieve physical activity goals at the individual level, which can reduce the risk of cardiovascular disease (Oja et al., 2011). Research shows that cycling for 1–60 minutes per week reduces all-cause mortality risk (Østergaard et al., 2018). Also, research has found that a higher level of cycling activity can improve mental health by reducing stress (Avila-Palencia et al., 2017). Switching to bicycle mode from a car also has financial benefits along with health benefits. Traveling by bicycle for a distance of 5km (5 days a week for 46 weeks in one year) the health savings amount to approximately 1300 euros annually (Rabl and de Nazelle, 2012).

Traffic congestion, air pollution, and noise pollution are common problems in cities (Melis et al., 2015). The mentioned problems are linked to the growing use of motorized mode, which makes cycling an attractive alternative (Nuñez et al., 2020). Traffic-related issues can be mitigated by promoting walking, cycling, and public transportation. This will help reduce the traffic volume, decreasing the overall environmental impact of motorized vehicles. Therefore, city authorities prioritize solutions that can help create a more flexible and sustainable transport system. In addition, changing travel habits and discouraging the use of private motorized vehicles are also found beneficial (Cafiso et al., 2022). Bicycles have additional advantages compared to motorized vehicles because they are affordable and, in traffic jams, can be faster (Zuo and Wei, 2019).

However, the comfort level experienced by bicyclists can significantly influence mode choice (Ahmed et al., 2023). Furthermore, the pavement surface quality often has a vital role in deciding the route preference to a destination for riders (Wang et al., 2018). Therefore, bicycle paths and lanes should be smooth, requiring minimum effort of the bicyclists (Bíl et al., 2015; Miah et al., 2019). When evaluating the best paths for bicyclists, pavement quality is frequently considered along with other relevant indicators, including road width, traffic volumes, and traffic speed (Gao et al., 2018). Hence, cycling comfort is becoming increasingly crucial for bicyclists and transport planners.

A bicycle infrastructure that is not well-maintained creates vibration, mainly perceived as uncomfortable by cyclists (Ahmed et al., 2023). The cyclists' perceived comfort while riding a bike is an important and critical factor influencing their preference for cycling (Rybarczyk and Wu, 2010). Various studies have been conducted that have assessed comfort for cyclists based on the roughness of bicycle paths or lanes. In order to thoroughly examine and understand methods available for assessing bicycle comfort based on vibration, it is crucial to conduct a literature review. This will help policymakers by providing a guide on reliable methods for evaluating cycling comfort.

2. Methodology

This section describes the methodology used for this review paper. A literature review paper is crucial in developing knowledge and scientific research (Makulilo, 2012). Also, it provides researchers and practitioners with an updated overview of existing research on the topic (Mariani et al., 2021). In addition, it presents guidelines for future studies. The below research questions were formulated, which will be answered throughout the paper:

- What are the methods available for assessing comfort based on bicycle vibration?
- What are the key components of the methods?
- How is the assessment for comfort done?

2.1. Search terms

A search protocol was established to search for relevant research articles. Key concepts were established before searching for relevant papers in the scientific databases. The concepts help in ensuring that the relevant research articles are not missed.

The search terms were broadly categorized as bicycling comfort and assessment. Alternative keywords were used for each term used in the search. The keywords were combined using the Boolean operators "OR" and "AND". An asterisk was also used to denote the beginning of specific letters. The asterisk looks for possible words such as cycl*, which can look for cycle and cycling. Possible synonyms, acronyms, and technical terminology were considered for keywords. Concept 1 includes bike-related terminologies, such as "bicycl*," "cycl*," and "bik*." The second concept includes terms like "comfort," "comfort assessment," "comfort perception," and "perceived comfort." While the third concept included terms like "vibration" and "acceleration."

2.2. Databases

Scopus, Web of Science (WoS), and Google Scholar databases were used to research relevant papers. Scopus and WoS provide coverage of peer-reviewed journals, ensuring access to high-quality and relevant research papers for the review. The Google Scholar database was utilized to ensure no important paper was missed in the selection process. Google Scholar returns many papers; a cutoff of 200 was set to look for relevant papers.

2.3. Study selection criteria

The literature review process should be transparent and avoid biases in selecting the studies for the literature review paper (Khandelwal et al., 2019; Pickering & Byrne, 2014). It should also be transparent in selecting research articles (Munir et al., 2021; Raad and Burke, 2018). We established inclusion and exclusion criteria to avoid biases in selecting the studies. It also helps reproduce the review results. After selecting keywords, the following stage was to examine and assess the research papers for inclusion based on criteria (inclusion and exclusion). The studies for review were selected based on the criteria below.

- Study designs: Studies that developed or assessed bicycle comfort based on vibration or vertical acceleration are included.
- Publication status: Peer-reviewed journals or conference proceedings.
- Publication type: Only primary studies are considered.
- Secondary publications: No secondary publications, i.e., Technical reports, review articles, research letters, research notes, book chapters, book reviews, editor's comments, and reader comments, were considered.
- Publication year: 2010-2024
- Language: Studies published in English.

2.4. Data extraction

The relevant data was extracted from the selected articles, focusing on a comprehensive understanding of the contents of the papers to address the research questions. The extracted information comprises the authors, publication year, country, assessment tool, source of the data, and study design.

3. Results

3.1. Overview of the Included Studies

The selected fourteen research articles used the vibration or roughness index to measure cyclists' comfort on the bicycle infrastructure based on vibration or verticle acceleration. Table 1 presents the general study characteristics of the selected studies. The research on cycling comfort extends across multiple countries. Based on Table 1, most of the studies are carried out in Europe. Two studies were conducted in China and Germany (Calvey et al., 2015; Gao et al., 2018; Gogola, 2020; Zhu and Zhu, 2019). The other countries where the studies were conducted are Denmark, Belgium, Sweden, Italy, Slovakia, Brazil, Singapore, Czech Republic, Scotland, and The Netherlands. The papers used two study designs, i.e., objective and mixed. Six studies used mixed methods (Ahmed et al., 2023; Bíl et al., 2015; Calvey et al., 2015; Gao et al., 2018; Shoman et al., 2023; Zhu and Zhu, 2019), while eight studies used objective methods only (Argyros et al., 2024; Cafiso et al., 2022; Gogola, 2020; Hölzel et al., 2012; Nuñez et al., 2020; Olieman et al., 2012; Wage et al., 2020; Zang et al., 2018).

Table 1. Summary of the selected studies.

Authors and year	Country	Method	Equipment used	Study approach
(Argyros et al., 2024)	Denmark	DCI	Bicycle lights, smartphone app, global navigation satellite system, bicycle airbag helmet	Objective
(Ahmed et al., 2023)	Belgium	Bicycle Comfort Mapping	Smart bicycle lights, questionnaire, smartphone app	Mixed
(Shoman et al., 2023)	Sweden	Behavioral Risk Indicator	Instrumented bicycle, questionnaire	Mixed
(Cafiso et al., 2022)	Italy	RMS, IRI	Smartphone app, automatic road analyzer, laser cracking measurement system	Objective
(Gogola, 2020)	Slovakia	Vibration and visual inspection	Smartphone app	Objective
(Wage et al., 2020)	Germany	DCI, IRI	Smartphone app (RideVibes), OSM	Objective
(Nuñez et al., 2020)	Brazil	BEQI, RMS	Video camera, smartphone	Objective
(Zhu and Zhu, 2019)	Singapore	CCI	Instrumented probe bicycle	Mixed
(Gao et al., 2018b)	China	DCC	Acceleration Data Logger, questionnaire	Mixed
(Zang et al., 2018)	China	IRI	Smartphone accelerometer, sensor data	Objective
(Bíl et al., 2015)	Czech Republic	DCI	GPS device, smartphone accelerometer, questionnaire	Mixed
(Calvey et al., 2015)	Scotland	Surface condition rating-scale	IntelliBike, questionnaire	Mixed
(Hölzel et al., 2012)	Germany	Rolling resistance	Pendulum	Objective
(Olieman et al., 2012)	The Netherlands	RMS	Inertial acceleration sensors, mounting brackets, GPS	Objective

3.2. Measurement equipment

Various innovative equipment and technologies have been employed to assess bicycle infrastructure and cyclist comfort. These studies entailed fieldwork; the most common technique applied was a cycle mounted with a GPS device and accelerometer or vibration sensors (Bíl et al., 2015; Calvey et al., 2015; Hölzel et al., 2012; Olieman et al., 2012; Wage et al., 2020; Zang et al., 2018; Zhu and Zhu, 2019). Others have used smartphone applications (Ahmed et al., 2023; Argyros et al., 2024; Casiano Flores et al., 2020; Gogola, 2020; Wage et al., 2020; Zang et al., 2018), and two studies have used smart bicycle lights (Ahmed et al., 2023; Argyros et al., 2024).

3.2.1. Instrumented probe bicycle

Instrumented probe bicycles have traditionally been used in bicycling research to assess the condition of cycling infrastructure. Fig.1 shows an example of the instrumented probe bicycle with sensors installed. A bicycle equipped with instruments and sensors (probe bike) was used to collect data in Singapore (Zhu and Zhu, 2019). The probe bike had a video camera and sensors, including an accelerometer, a GPS device, and a gyro sensor. Another system, known as the DCC system, consisting of three parts, was developed, which had an accelerometer, GPS with a smartphone, and a bicycle (Gao et al., 2018). The accelerometer adopted a HOBO Pendant G Acceleration Data Logger (a three-channel logger) with a resolution of 8-bit. The device can record 21,800 three-dimensional acceleration readings (x, y, and z-axis). Similarly, an IntelliBike accelerometer was used to assess bicycle pavement. This system consists of a bicycle accelerometer which can differentiate between various surface qualities based on its data (Calvey et al., 2015).

Fig. 1. Example of an instrumented bicycle with sensor details source: (Shoman et al., 2023)

The instrumented probe bicycle system developed by (Olieman et al., 2012) consisted of inertial sensors to measure the vibrations, mounting brackets to attach these sensors to the bike, and a GPS receiver. ProMove2 wireless nodes from Inertia Technology were used as inertial sensors, while Garmin Edge 705 was used as a GPS receiver. Shoman et al. (2023) recently used sophisticated bicycles equipped with multiple sensors and devices to collect data, including an accelerometer, a gyroscope, an inertial measurement unit, an absolute encoder, hall effect sensors, an inclinometer, video camera, incremental rotary encoders, GPS, compass, speed sensor and, mobile eye tracker (Tobii Pro-Glasses 2).

3.2.2. Smartphone application

With the advancement of electronic devices like smartphones, integrating sensors embedded in them with georeferencing has become simpler. These smartphone sensors can be used for cycleways' inventory and evaluation. Smartphone applications have proved to be practical tools for gathering information on road roughness utilizing the GPS data and vibrational or acceleration sensors available on these devices. The use of smartphone applications was very popular in the studies selected for the review, as six studies used it (Ahmed et al., 2023; Argyros et al., 2024; Casiano Flores et al., 2020; Gogola, 2020; Wage et al., 2020; Zang et al., 2018).

Various studies have used mobile apps from the Apple and Google stores that use mobile sensors for collecting data. One study used the Phyphox app to collect vibration data (Gogola, 2020). A visual inspection was carried out to verify the recorded vibration through the app. High vibrations were mainly caused by curbs, bumps, and the rough texture of paved surfaces (where the asphalt is cracked). The study demonstrated the potential use of smartphone apps in bicycle pavement assessment. Also, a difference was noted in the vibration levels on various pavement smoothness levels (unpaved, paved, and cracked paved).

Some studies have developed dedicated applications for measuring bicycle vibration. "RoadSR" and "RideVibes" are examples of the developed software (Wage et al., 2020; Zang et al., 2018). The vibration data collected on these mobile applications can be used in standardized roughness metrics like the IRI and DCI. One study also created an algorithm to detect potholes and road humps (Zang et al., 2018). The accuracy of the algorithm was confirmed through drone-captured images.

Recently, two studies have used mobile applications with smart bicycle lights (Ahmed et al., 2023; Argyros et al., 2024). Ahmed et al. (2023) used SEE.SENSE app which is very useful in identifying dangerous locations on bicycle paths. The app can also be used to collect cyclist perception. The other study used two mobile apps, one for collecting accelerometer data (connected through GNSS data) and another app, Hövding, to gather the trajectory data (Argyros et al., 2024). Similarly, another study utilized Android mobile applications on bicycles and e-scooters to collect acceleration and position data (Cafiso et al., 2022).

3.2.3. Smart bicycle lights

Two studies have used smart bike lights as novel platforms to collect vibration data (Ahmed et al., 2023; Argyros et al., 2024). Mounting these lights on a bicycle, one in the front and one at the back (e.g., SEE.SENSE), effectively records the cyclist's journey attributes, such as bicycle speed, vibration, latitude, longitude, etc. The lights must be connected to the app to collect the data accurately. Another study used Findr (intelligent bicycle lights) to collect data on pavement roughness (Argyros et al., 2024). They also collected bicycle trajectory data for which another app (Hövding) was used. This app was connected through an airbag helmet. The combination of these two mobile applications and the equipment (airbag helmet and Findr lights) can gather data on surface roughness on the bicyclist's traveled path. The recording frequency of vibration measurement is 50 Hz. The DCI method developed by Bíl et al. (2015) was used for data analyses. Ahmed et al. (2023) used a mixed approach, using the vibration data from smart bicycle light data (SEE.SENSE ACE device) and bicyclist perception to make cycling comfort mapping. GIS was utilized to make cycling comfort maps, which help to visualize the bicycle infrastructure comfort levels (Ahmed et al., 2023). The SEE.SENSE ACE device is a highly sensitive three-axis accelerometer that can record up to 800 readings in one second. The vibration values range from 0-100.

3.3. Comfort assessment methods

Once the data is collected using the sensors, the cycle infrastructure is rated based on the collected data. Two types of study design are used (mixed and objective). Objective studies solely depend on the data collected from the sensors, while the mixed approach (combining objective and subjective evaluation) uses cyclists' perceptions and the data from the sensors. Some studies relied on already established methods like IRI and RMS, while others developed their own methods; for example, Bíl et al. (2015) developed DCI to assess bicycle path comfort. The DCI only considers the verticle acceleration values greater than 1 in a single second from the recorded verticle acceleration values. Other studies have used the DCI (Argyros et al., 2024; Wage et al., 2020). The DCI value ranges from 0-1, a value closer to 1 suggesting better comfort for cyclists. The study results suggest that the mean DCI for asphalt was 0.8132, and for old granite, cobblestone was 0.3861 (Bíl et al., 2015). The DCI also considers cyclists' perception of vibration. The study results show a very strong correlation of −0.94 between DCI values (objectively measured) and cyclist perception (subjectively measured). Ahmed et al. (2023) also consider the perception of cyclists in the comfort cycling map. They found a positive relationship between the objectively collected data and subjective perception of comfort on the cycling path. The subjective and objective data were used to make cycling comfort maps for the study area.

The RMS technique is based on the root mean square of accelerations in y axes used to analyze the vibration levels. Nuñez et al. (2020) utilized ISO 2631-1 recommendations to analyze comfort perceptions for different vibration levels. In addition, BEQI was also utilized. The test results on three types of pavements (asphalt, concrete, and concrete bricks) showed that the acceleration values were lowest for concrete pavement. RMS is also used in other studies by Cafiso et al. (2022) to see its correlation with IRI results. The IRI usually requires an advanced dedicated probe car; however, it was adopted for bicycles by removing the parameters needed for a car (Zang et al., 2018). Other important roughness methods are CCI and DCC (Gao et al., 2018; Zhu and Zhu, 2019). Both methods also consider the perception of cyclists. The CCI is based on the videos of the bike path captured via a video camera mounted on a bike.

This method does not involve direct manual observation or digital tools like OSM. Collecting data using a video camera is efficient and requires less time. The video data was later used to calculate the relationship between CCI and the subjective perception of bicyclists. The CCI was derived using the XGBoost method, which provided higher accuracy than the commonly used methods, such as the ordered probit model (Zhu & Zhu, 2019). The DCC considered the vibration levels on the bicycle using four wireless sensors to measure acceleration in real-time. Based on the experiments, a strong relationship was found between the level of vibrations and bicycle speed.

4. Conclusion

Worldwide, promoting bicycle use is advocated to mitigate the adverse effects of motorized transportation, for example, growing traffic congestion, ever-increasing noise, and air pollution. Making cycling an attractive mode of transport requires the bicycle infrastructure to be comfortable and along with being safe. Various approaches have been developed over the years to assess the comfort level of bicycle infrastructure. Through this literature review, we aim to explore state of the art on vibration analysis used to assess the comfort of bicyclists.

The findings of our review showed that various approaches have been developed for assessing the comfort of bicycle paths based on vibration or vertical acceleration. The selected studies have used objective and mixed methods. The objective evaluation depends only on sensor data. The cyclist's perception of vibration is considered in the mixed assessment approach. The studies have found a good correlation between the objective measure and the subjective comfort feeling of the cyclists. The techniques such as IRI, DCI, and RMS are often used to assess cycling comfort.

Some research has used complex systems such as Pendulums and inertial sensors (Hölzel et al., 2012; Olieman et al., 2012). The problems associated with such technology include replicability and practical use. Such complex systems require technical knowledge to configure the equipment, conduct experiments, and obtain the required results.

Researchers have incorporated more sophisticated tools like sensor-equipped bicycles (instrumented probe bicycles) and mobile apps to conduct evaluations as technology advances. Some of the most common sensors used in instrumented probe bicycles include accelerometers, GPS, and gyroscopic sensors. The instrumented bikes create an abundance of data about bicycling tracks. It is sometimes challenging to merge the data from different sensors. In addition, the reproducibility of the results for other researchers can also be complicated (Bíl et al., 2015). Another drawback is the bike's cost, which is usually very expensive. Some studies have used mobile phone applications to collect vibration or verticle acceleration data. The apps use the built-in sensors in the smartphones. This approach offers an alternative to the expensive instrumented probe bicycles.

Two studies have also shown that smart bicycle lights can collect pavement data. Smartphone apps and smart bicycle lights provide a cheap alternative to technologically complex and expensive systems. The method used by Ahmed et al. (2023) and Argyros et al. (2024) shows a considerable improvement in the efficient and scalable data. Combined with bicycle lights, these apps are useful in detecting road roughness, defects, and potholes. Also, The capacity to regularly monitor and reassess specific segments of bicycle routes could offer a more comprehensive understanding of surface degradation over time.

This research reviews the tools or methods used in literature to guide urban planners and policymakers. The paper provides an overview of how bicycle infrastructure can be assessed. Using the methods, the locations that need improvements can be identified. The city authorities can improve the identified location. The improved infrastructure increases the comfort of bicycle paths, lanes, and routes. This can encourage more people to adopt bicycling as a sustainable mode and ultimately enhance the overall quality of urban life.

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