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The effect of bicycle road surface on cycling energy consumption

Abstract: The advantages of using a bicycle as a mean of transport for daily urban journeys increase the demands of cyclists for efficient and comfortable mobility. One of the basic elements that allows to reach the required target efficiently is the appropriate bicycle infrastructure, including the type of road surface. Thus, the authors have taken up the problem of the effect of the type of pavement on cyclist's energy expenditure. The article presents the growth rate of bicycle traffic on the basis of measurements carried out in Wroclaw. The types of surface of bicycle paths have been briefly described. The results of own research on the energy expenditure of a cyclist depending on the type of pavement were presented. On the basis of the analysis, the most effective type of surface and the relative differences between the different types.

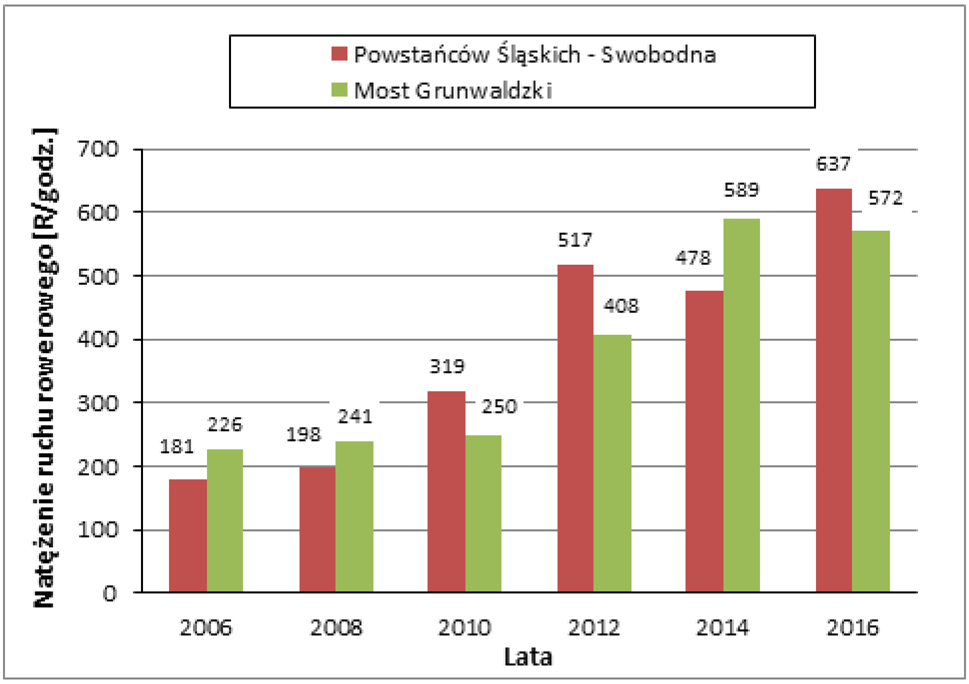
Keywords: Cycling traffic; Surface of the cycling path; Energy expenditure of a cyclist

Introduction

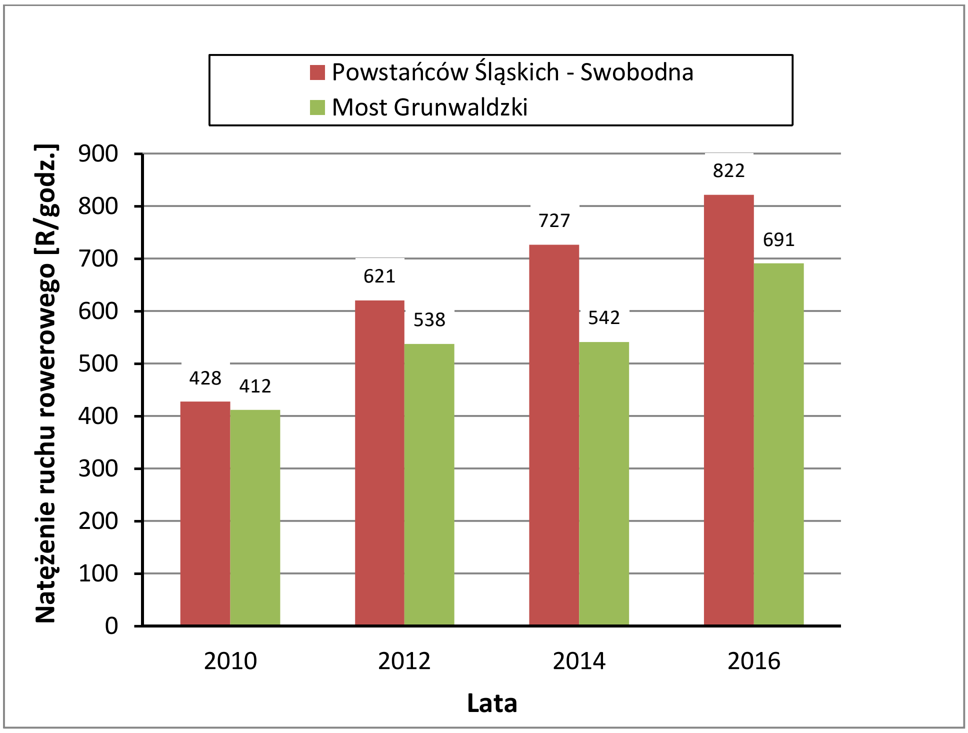
A bicycle is an important element to support the sustainable urban transport system, which may be helpful in partially discharging communication problems in large cities. Bicycle communication is environmentally friendly, has health benefits for the user, generates low investment and operating costs [4, 6, 23] and is the fastest means of transport for up to 6 km in urban environments [11]. The degree of use of a bicycle depends on the availability and scope of bicycle infrastructure, which are: bicycle availability, (public, private), bicycle lanes, bicycle parking lots, self-service bicycle repair stations [18]. The bicycle path should meet the requirements of ensuring that cyclists are comfortable and comfortable. The presented expectations are related to low rolling resistance and vibrations transmitted to the cyclist. These characteristics are largely dependent on the type and condition of the road surface. The key issue to be resolved is the extent to which safe cycling traffic can function in a shared space with other road users. Wroclaw has a concept of development of cycling routes [10] and design and execution standards for the cycle route system of the city of Wroclaw [27]. The basic concept of the Concept is to achieve 100% availability of the main sources and destinations in the city area using the bicycle and to present the principle of hierarchization of the importance of bicycle paths, broken down into classes: main, collective, local and recreational. The design and implementation standards include general guidelines to be met by cycling infrastructure and take account of the requirements of [20 and 26]. Applicable to the requirements for the design of bicycle paths. Regulation (26) defines in general terms technical requirements for the location of cycling equipment in the lane, provided that the requirements for the design of pavements, including bicycle paths (Appendices 4 and 5), have been repealed by the Regulation [25]. The lack of solutions recommended by the Ministry of Infrastructure has forced local authorities to develop their own standards for the construction of bicycle paths, eg [5, 6, 7, 8, 9]. However, they relate to a considerable part of functional expectations, bicycle path classification and their parameters Geometric, but less in terms of surface quality, recommending a priori bituminous surfaces. The disadvantage of the adopted solutions is their weak legal position, which makes it difficult to control and enforce the requirements of the Standards. In addition, the presented solutions often take into account the problem of the type of pavement and its quality in a very generalized manner. In the last 20 years, the length of the network of bicycle paths has increased steadily, for example in 1995 in Wroclaw was 20 km and in 2015 already 229.78 km [34]. The surface network of cycling routes are the most frequently surfaces: asphalt, concrete - with concrete tiles or dice [30] and compacted mixture of mineral - stone. Changes in the intensity of cycling at selected intersections located on access routes to Wroclaw city center are presented in tab. **1** and Figs. **1** and **2**, using the results of the research presented in the study [2]. Measurements were conducted in June 2006 in the years 2016 to 2016 for the City of Wrocław by the Association of City Action.

Tab. 1. Breakdown of traffic intensity at selected intersections at morning and afternoon rush hours in June [R/h]

Hours	7.00 ÷ 8.00						16.00 ÷ 17.00			
Years / Crossing	2006	2008	2010	2012	2014	2016	2010	2012	2014	2016
Powstańców Śląskich, Swobodna	181	198	319	517	478	637	428	621	727	822
Most Grunwaldzki	226	241	250	408	589	572	412	538	542	691



1. Changes in the intensity of cycling in the early morning in hours 7.00 ÷ 8.00 in years 2006 ÷ 2016



2. Changes in the intensity of cycling in the afternoon in hours 16.00 ÷ 17.00 in 2010÷ 2016

From the presented statement, it follows that there is a systematic increase in interest in the use of a bicycle for urban trips. According to the Wroclaw Comprehensive Traffic Research in 2010 [16], more than 3.5% of city trips were carried out using a bicycle. In some EU countries, cycling in urban areas was 32% in Copenhagen, 25% in Amsterdam. The necessity to achieve such a share of cycling is to provide appropriate transport policy for the shaping of changes: urban mobility [17] and the development of broad bicycle infrastructure in relation to: the development of bicycle routes, urban bicycles [14]: personal; for children; luggage transport, self service stations, bicycle repair services, bicycle parking and bicycle storage. In urban conditions, the bicycle becomes an alternative to other means of transport. There is a systematic expansion of the cycling infrastructure [15 and 33], and bicycle users are beginning to articulate their expectations about the quality of the bicycle paths. This forces the use of materials that provide the surface with little rolling resistance, no vibration. The aim of the study is to compare the energy consumption of a cyclist on selected types of bicycle road surface in a good technical condition, without unevenness and damage, i.e. after being commissioned. Conducted testing of the bike lanes surface not exposed to car parking, i.e. located independently of the road for other vehicles.

Types of bicycle lanes surfaces

The comfort and safety of cycling traffic depend on the way the bike run in the cross-section and the quality of the road surface. The most common ways of driving traffic are the following [4]:

a) traffic is shared with other vehicles regardless of the traffic conditions,
b) bicycle lanes separated from existing roads,
c) on foot - cycling roads, usually run parallel to the existing roadway, common to pedestrians and cyclists,
d) cycle routes, along the existing roadway, with simultaneous separation from the road,
e) separate cycle lanes run independently of existing roadways and pedestrians, often with no collision crossings with other roads,
f) countercrossing, i.e. "upstream" lanes that allow cycling on one-way streets in the opposite direction to the traffic of motor vehicles,
g) cycling traffic takes place on a common carriageway with vehicles in the case of streets with traffic calming.

The Act on Road Traffic [32] only in special cases, allows for the use by cyclists, sidewalks for pedestrians. Driving comfort is also affected by safety, lack of obstacles, smoothness of the road, surface equality, energy demand and vibration from the surface to the biker, ie features that reflect the surface quality. According to the tilted [25] Annex 4 and 5 of the Ordinance of the Minister of Transport and Maritime Economy of 2 March 1999. [26] recommended designs for bicycle lanes were 2 types of surface: asphalt on the foundation of aggregates and concrete blocks on the foundation of sand both coarse and coarse, both with a thickness of 13 cm, placed on a non-graded substrate of Group G1 or a substrate substrate for a layer of thickness 10 cm for the load group G2 and G3, and 20 cm for the load group G4. Under national conditions, in many studies commissioned by local governments, it is recommended to use bituminous pavements, but in practice, the following types of pavements are also used for the construction of bicycle paths:

a) non-bevelled concrete block,
b) concrete blocks bevelled,
c) concrete,
d) stone block,
e) stone slabs of various shapes, especially in the old town areas of large cities,
f) mineral-rock mixture made of non-mechanically stabilized layer, they are most often found on bicycle paths used for recreational and seasonal traffic, e.g. in parks and on flood embankments.

The surface of the bicycle path should be characterized, among other things, by the minimum energy demand of the cyclist, which is a result of rolling resistance depending on the type of surface and quality of work and lack of shocks transferred from the surface to the cyclist. In the paper [19] the impact of different types of pavement on the health of the cyclist was determined. It has been demonstrated that, when using a bicycle for daily and long-term travel (over 3 ÷ 4 hours), some types of pavement may pose a risk to the health of the cyclist in relation to joint and wrist muscles damage. Work [13] compares the energy consumption of a cyclist, assuming a demand for energy for high-quality asphalt pavement as 100% for asphalt pavement with 120% damage, uneven concrete pavement surface of 130% unpaved, uneven and bumpy pavement aspherical concrete as 140 %.

This paper discusses the results of studies related to the determination of energy consumption by a cyclist for selected surfaces in good technical condition without unevenness, rutting, damage and no maintenance.

Scope of the study

The cyclical energy expenditure associated with cycling (i.e. bypassing the energy required to maintain the vital functions of the body) is influenced by the following factors

a) inertia resistance - associated with speed variation (acceleration),
b) gravity resistance - associated with uphill rides,
c) aerodynamic resistance - proportional to speed,
d) internal resistance of bicycle mechanisms,
e) rolling resistance.

Of the above-mentioned resistances, some of them can be omitted in the analysis by providing the appropriate experimental conditions. No gradation of gravity, depending on the elevation, is made during rides with the highest possible zero inclination. On the other hand, driving at the steady speed eliminates the inertia resistance and the aerodynamic drag remains constant. Driving at a constant speed further reduces the effect of speed on the internal resistance of the bicycle mechanisms and on the rolling resistance..

Finally, the influence of rolling resistance on the speed of cycling in urban conditions depends on: tire air pressure, tread type, and type of pavement [21]. The effect of tread type and tire pressure was eliminated using the same tread type and constant tire pressure. This resulted in a negligible effect of other factors, other than the type of surface, on the energy expenditure of the cyclist. The values of rolling resistance coefficients for different surfaces are shown in Table **2**. Less rolling resistance generates less energy required to drive a single section of the road.

Tab. 2: Rolling resistance coefficients for passenger cars and bicycles

L. p.	Type of surface	Car, tire with inner tube [1, 3, 4, 22]	Bicycle tires [28, 35, 36]
1	Mineral asphalt mix	0,010 ÷ 0,012	0,004 [28] 0,003 ÷ 0,007 [34,36]
2	Concrete cement	0,012 ÷ 0,015	0,002[35]
3	The equal granite block	0,014 ÷ 0,016	0,010 [36]
4	Gravel surface in good condition	0,020 ÷ 0,023	0,013[36]
5	Concrete bevelled brick	0,01 ÷ 0,015	-
6	Concrete non-bevelled brick	-	0,006 ÷ 0,007 [36]
7	Wooden track	-	0,001 [35]
8	The humid sandy road	0,080 ÷ 0,150	-
9	Dry sand	0,150 ÷ 0,300	0,022 ÷ 0,041 [34]
10	Grassy ground	0,060 ÷ 0,110	0,007 ÷ 0,012 [34]
11	Resistance steel wheels on rails	0,001 ÷ 0,002	0,001 ÷ 0,002 [35]

Rolling resistance coefficients for cycling tires are given according to [28, 35, 36], where test conditions are not met, so it is appropriate to carry out tests under prescribed conditions for the surface and attributes of the bicycle used (bicycle type, shock absorbers, tire pressure, size and type tires).

The study was carried out in Wroclaw on sections of bicycling roads located outside the road for vehicles, in the months October - November 2016 in windless weather, at ambient temperature in the range of +5 to +20 ° C, on pavements of width ≥ 1.5 m in technology with (fig. **3**):

a) asphalt concrete,
b) non-bevelled concrete brick (type holland 10/20cm),
c) bevelled concrete brick (typu behaton),
d) a mechanically compacted stone mixture,

characterized by a good technical condition, without defects and irregularities, providing comfort.

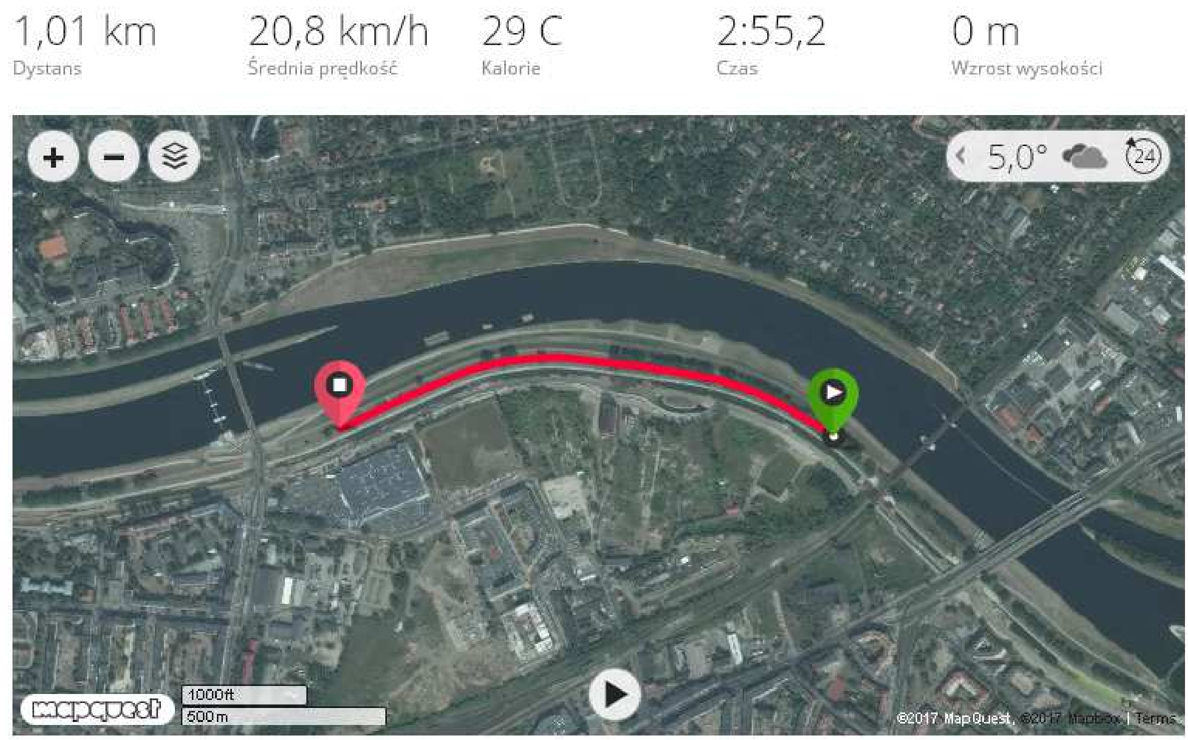
Asphalt concrete | Non-bevelled concrete brick | Bevelled concrete brick | Stone mix

3. View of the tested surfaces

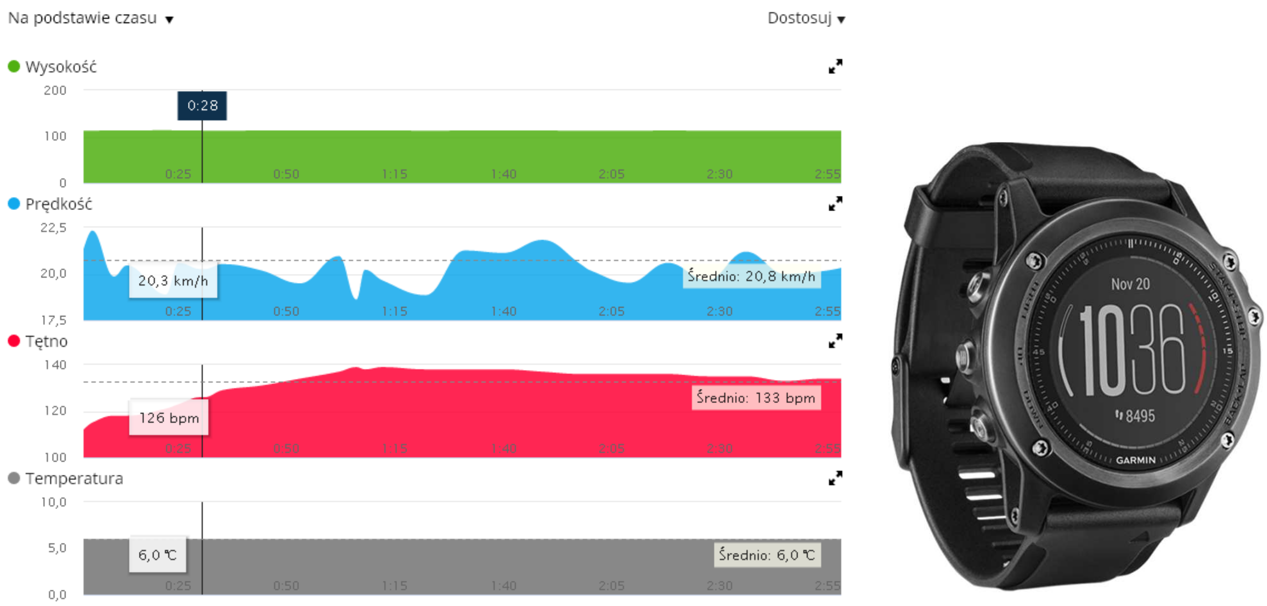
The total length of the tested roads was 146 km. Length of the tested sections for each type of surface ranged from 0.5 km to 2.2 km. The average length of the test section was 0.83 km. The measurements were carried out in a time not exceeding 2 hours. The study was conducted by one cyclist. The Giant City Bike was used without amortization (photo **4**) on Schwalbe Silentio tires of 42-622 (28 × 1.60-700 × 40C) at 4 bar tire pressure.

4. View of the bicycle used for research

Discussion of research results
Garmin fenix 3 / HR device (fig. **6**) was used to measure the ambient temperature, current and average speed, distance traveled, and cyclists' heart rate (measured by the chest strap). The built-in GPS receiver allows you to visualize the route and its longitudinal cross-section (Figures **5** and **6**). Determining the energy used by the cyclist is based on the current pulse rate. 137 measurements were taken, the average speed during the test was 20.2 km / h. On all cross-country bikes, there were curbs in the cross-section of 2 cm high.

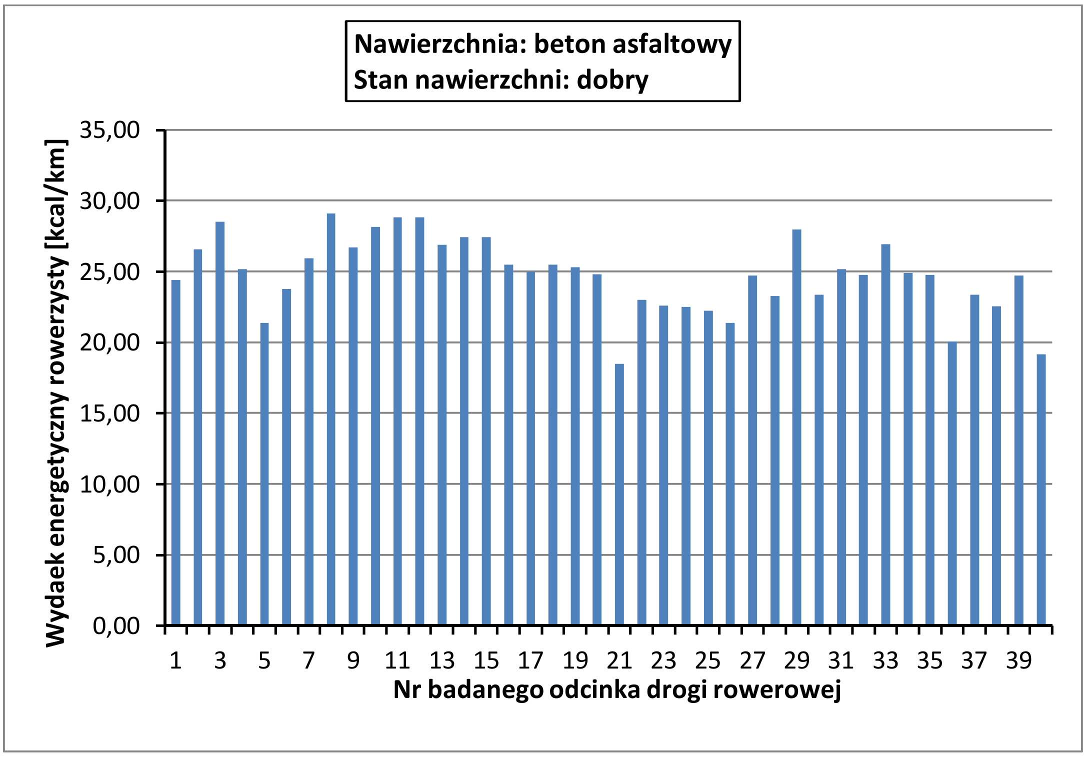


5. An example of the test section location recorded with the measuring device

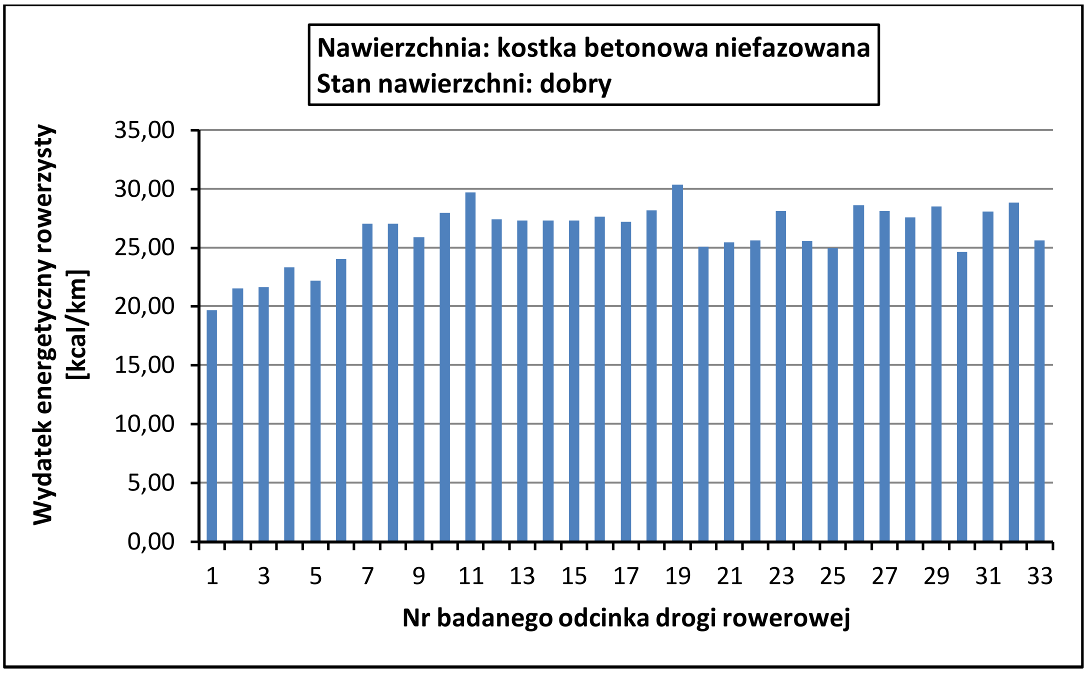


6. Record of test results and view with measuring device

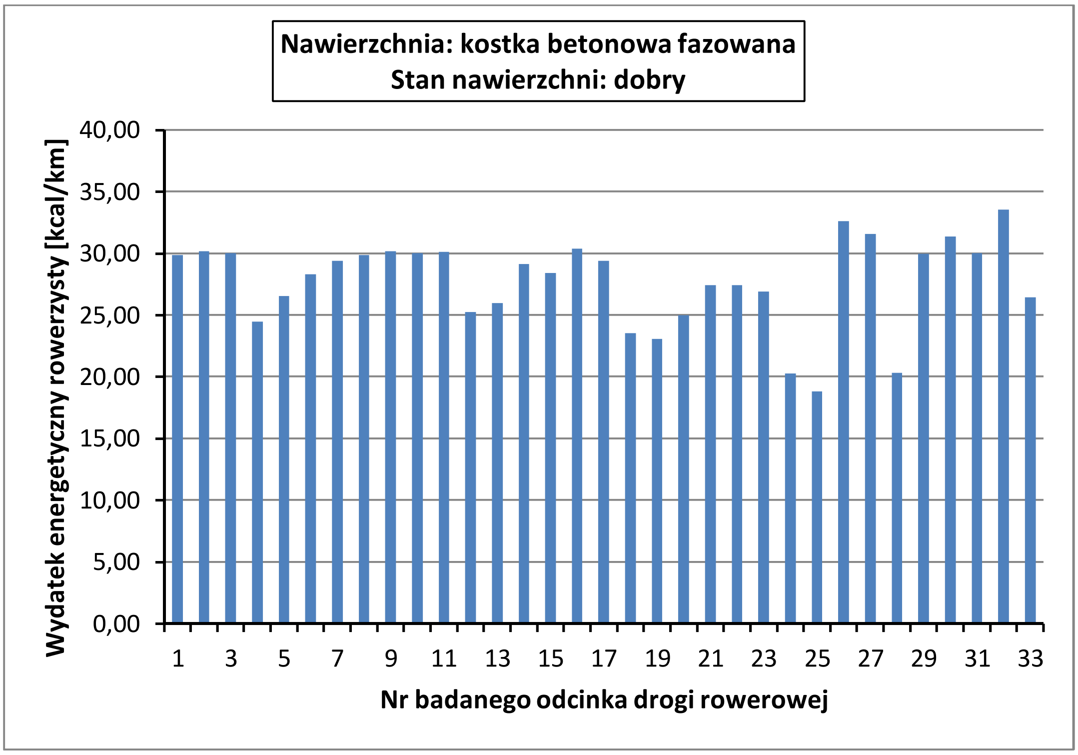
As a result of the studies, the value of cyclist's energy demand [kcal] was determined to be 1 km of the cycle path depending on the type of pavement. The results are presented in figures **7 to 10** and are presented in the table **3**.



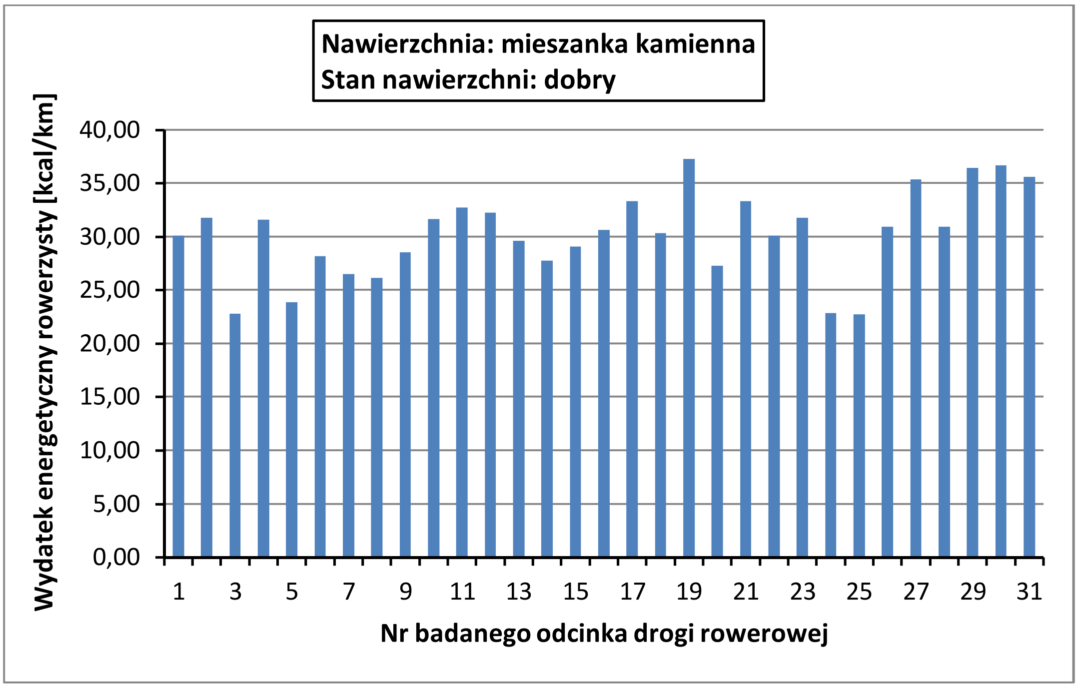
7. Change of cyclist energy consumption for surface made of asphalt concrete surfaces



8. Change of cyclist energy consumption for surface made of non-bevelled concrete brick



9. Change of cyclist energy consumption for surface made of bevelled concrete brick



10. Change of cyclist energy consumption for the surface made of stone mix.

Tab. 3: Collation of the energy of the cyclist to ride 1km of a bicycle lane with a specific surface.

Characteristics of tested parameters	Surface made of asphalt concrete	Surface made of non-bevelled concrete brick	Surface made of bevelled concrete brick	Surface made of the stone mixture
The average value of energy demand [kcal/km]	24,79	26,30	27,76	30,28
Percentage increase in energy consumption compared to asphalt concrete surfaces [%]	----------	6	12	22
Minimum value of the energy demand [kcal/km]	18,50	19,68	18,81	22,76
Maximum value of the energy demand [kcal/km]	29,13	30,37	33,58	37,31
Standard deviation of the energy demand distribution [kcal/km]	2,63	2,48	3,57	4,02
The coefficient of variation of the energy demand distribution [%]	11	9	13	13
Number of tested sections	40	33	33	31

Summary

The surface of the bicycle path should provide safety and fluidity for the cyclist, minimizing physical effort resulting from the need to brake and accelerate the quality of the surface. The most advantageous of the tested surfaces are bituminous pavements, because of the least demand for cycling power (table **3**) and in particular for the amount of vibration transmitted to the cyclist [19]. In the paper [24], it has been pointed out that in the Netherlands, bituminous pavements are used on off-road cycling routes and on urban roads of high importance in the transport system, e.g. on interstate highways or high traffic.

The results of the research on the surface in good condition without damage, unevenness, and bumps showed no difference in the demand for bicycles compared to asphalt concrete, up to 6% for non-bevelled concrete brick, 12% for bevelled concrete brick and 22% for stone mixe. In works [12, 29], the authors describe the increased energy consumption of the cyclist by 30 ÷ 40% for concrete brick compared to asphalt, except for concrete used for exploited uneven and bumpy concrete brick [31]. Bituminous surfaces other than having a discontinuous structure cause vibrations that can affect the health of the cyclist, as is specified in the domestic conditions at work [19]. The vibrations transmitted from the surface to the cyclist, especially when extended and systematic, may be a greater reason for the discouragement of bike users to the concrete pavement in favor of asphalt pavements. The comfort of the bike is also dependent on the quality of the surface, which should be equal, not surrounded by bushes growing into the extreme of the bike path. For increased interest, the use of a bicycle for daily driving is more likely to have, not the type of pavement (brick or asphalt concrete) but its technical state determined by:

a) undulations exploited surface in reference for each of its kind,
b) Point obstacles, e.g. uneven manholes intakes, surface bumps, trees and bushes growing under the surface,
c) linear obstacles, e.g.: the presence of roadside plantings in the gauge of the roadside causing driving speed limitation,
d) no elevation in the area of intersection or exit from the property, bike path to the pavement level,
e) the necessity of repeatedly stopping the cyclist in the crossing area in particular with traffic lights for left-handed off-road for the vehicles.

The problems related to the influence of the type of pavement, its operating characteristics and the quality of maintenance on the comfort and safety of cycling are discussed further in the domestic conditions.

Source materials

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