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# BICYCLE FREE-FLOW SPEED ESTIMATION BASED ON GPS DATA – COMPARISON OF BIKESHARING SYSTEM AND STRAVA DATA

**Sylwia PAZDAN[1], Mariusz KIEC[2]**

[1, 2] *Cracow University of Technology, Faculty of Civil Engineering, Cracow, Poland*

## *Abstract:*

*The increasing number of cyclists in cities around the world results in a greater focus on bicycle traffic. Next to traffic volume, the main characteristic of traffic used in road safety analysis, infrastructure planning, design, etc. is its speed. Bicycle speed is strongly affected by the type of bicycle facility, motor vehicle traffic parameters (volume, speed, share of heavy vehicles), trip motivation, weather conditions, etc., and therefore it is difficult to estimate. Traditionally, bicycle speed is determined directly using speed radar or indirectly, as a quotient of measurement base length and travel time calculated using a stopwatch or video technique. There are also researches where bicycle speed was estimated based on GPS sources, mainly mobile apps. However, depending on the GPS source and the group of cyclists, bicycle speed gained from GPS data can be different from the speed of regular cyclists (due to different levels of experience or types of bicycle). In the paper, the relationships between bicycle speed obtained from empirical measurements and two different GPS sources, which were bikesharing system (Wavelo) and Strava app, were analysed. In total 18 research sites were selected different in terms of bicycle facility (bicycle path, shared pedestrian/bicycle path, contraflow lane) and element of road network (road segment, bicycle crossing with or without traffic signals). Two-tailed test for two means was conducted to analyse the statistical significance of differences in bicycle speed estimated based on GPS data and empirical measurements using video technique. It showed that Wavelo and Strava speeds are by 17.4% lower are by 23.1% higher than the speeds of regular cyclists respectively. Two linear regression models describing relationships between bicycle speeds from empirical measurements and GPS data were developed. The results show that the variance of bicycle speed is almost 80% described by the variance of Wavelo speed and 60% described by the variance of Strava speed, which suggests that bicycle free-flow speed can be estimated based on GPS data either from bikeshare system or dedicated app.*

***Keywords:*** *bicycle speed, bikesharing system, Strava, big data*

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**Contact:**
1) sylwia.pazdan@pk.edu.pl [https://orcid.org/0000-0001-6106-7768] – corresponding author; 2) mkiec@pk.edu.pl [https://orcid.org/0000-0001-9193-7269];

## 1. Introduction

Next to traffic volume, the main characteristic of traffic used in road safety analysis, infrastructure planning, design, etc. is its speed. In opposite to motorized traffic, bicycle speed data is difficult to obtain. The reason is that cyclists' speed is strongly affected by type of bicycle facility (Bernardi and Rupi, 2015; Romanillos and Gutiérrez, 2020; Knight and Charlton, 2022), motor vehicle traffic parameters (traffic volume, speed, share of heavy vehicles) (Clarry, Faghih Imani and Miller, 2019), trip motivation and weather conditions (Strauss and Miranda-Moreno, 2017; Pazdan, 2020), etc. As a result, bicycle speed can change rapidly in different locations. Manual speed measurements are relatively expensive and time-consuming. Moreover, cyclists can ride on bicycle facilities, sidewalks, or roadways, which is an obstacle to the use of automatic counters. Therefore, GPS data is currently often used in research.

Bicycle GPS data are mainly obtained from GPS units (El-Geneidy, Krizek and Iacono, 2007) or mobile apps (Strauss and Miranda-Moreno, 2017; Clarry, Faghih Imani and Miller 2019; Saunier and Chabin, 2020). However, the capability of using bikesharing system GPS data in bicycle traffic analysis was not fully verified. Mobile apps e.g. Strava, are mainly used by experienced cyclists, who may ride at higher speeds. Bikesharing system can be used by tourists not familiar with bicycle facilities and traffic in the city, and therefore their speed may be lower. Additionally, for example in Krakow (Poland) public bicycles were heavier and had less number of gears (i.e. 3) than regular bicycle, which could also affect their speed. Therefore, irrespective of the source of bicycle GPS data, when analyzing bicycle traffic, the relationship between traffic parameters (including speed) of all cyclists and group of cyclists from whom GPS data was collected has to be determined. Authors do not know any research where those relationships were evaluated.

The aim of the paper was an evaluation the relationship between bicycle free-flow speed observed during empirical measurements and bicycle speeds calculated based on GPS data. Two GPS data sources were analyzed, which were bikesharing system (Wavelo) and Strava app. Analysis was made for the city of Krakow (Poland). The type of bicycle facility (bicycle path, pedestrian/bicycle path, contraflow lane) and element of road infrastructure (road segment and bicycle crossing) on cyclists' speed were analyzed. Linear regression models enable the estimation of bicycle speed based on GPS data were presented.

The paper is a supplement of research on using GPS data in bicycle traffic parameters estimation, which first part related to bicycle traffic volumes was presented in (Pogodzinska, Kiec and D'Agostino, 2020) and (Pazdan, Kiec and D'Agostino, 2021).

## 2. Literature review

The review provided by (Allen et al., 1998) showed that bicycle free-flow speed is in the range of 10-28km/h, with the majority of observations in the range of 12-20km/h. Similar results were presented in (Kovaceva, Wallgren and Dozza, 2022).

Bicycle speed depends on the type of bicycle facility. In (Strauss and Miranda-Moreno, 2017) it was found that average bicycle speed is highest on bicycle track (20.5km/h), lower on bicycle path (19.1km/h), and the lowest with no bicycle facility (19.0km/h). According to (Bernardi and Rupi, 2015) bicycle speed varies between 14.6-18.9 km/h on separated facilities and between 16.8-22km/h in mixed traffic. The standard deviation of bicycle speed was found to be 2.97-3.16km/h and 4.24-5.08km/h respectively. In (El-Geneidy, Krizek and Iacono, 2007) average bicycle speed was 16.25km/h, 15.62km/h, and 15.75km/h on off-street facilities, on-street facilities, and regular streets respectively. Based on (Rios et al., 2021), the implementation of bicycle lanes results in a 30% increase of average bicycle speed.

Male cyclists ride with higher speeds than females by 1.07-1.75km/h (El-Geneidy, Krizek and Iacono, 2007; Thompson et al., 1997; Parkin and Rotheram, 2010; Strauss and Miranda-Moreno, 2017; Romanillos and Gutiérrez, 2020; Poliziani, Rupi and Schweizer, 2022; Cubells, Miralles-Guasch and Marquet, 2023). Males' speeds are also more heterogeneous than females'. According to (Thompson et al., 1997) standard deviation of speed was 3.9km/h and 4.5km/h for females and males cyclists respectively. Additionally in (Thompson et al., 1997) children 13 years old and younger were found to travel with a mean speed of 14.3km/h, by 1.3km/h slower than older cyclists. However, results presented in

(Strauss and Miranda-Moreno, 2017) show that cyclists up to 25 years old achieve higher speeds than cyclists 44 old or more.

High skilled cyclists travel at higher speeds than beginners (Alhomaidat and Eljufout, 2021). According to (Poliziani, Rupi and Schweizer, 2022) frequent cyclists' speed was found to be on average by 5% higher than infrequent cyclists'. In (El-Geneidy, Krizek and Iacono, 2007) more experienced cyclists (who feel comfortable traveling in heavy traffic) were found to ride at a speed of 17.36km/h, which was by 2.26 km/h higher than people who were comfortable traveling only on off-street facilities.

In (Saunier and Chabin, 2020) bicycle speed was analyzed in reference to Traffic Analysis Zones (TAZs). The average bicycle speed equal 16.6km/h with a standard deviation of 0.61km/h remained stable over the day. Its daily variability was lower than for cars. However, it was found that the average speed is lower in the downtown than in the more peripheral areas of the city. Results presented by (Jensen et al., 2010) show that in weekdays average speed of bikesharing system users varies in the range of 11.2-14.5km/h, and is highest in the morning peak hours. During weekends is slightly lower between 10.3km/h and 14.0km/h. According to (Strauss and Miranda-Moreno, 2017) average bicycle speed is 20km/h, 19.4km/h, and 18.2km/h on arterial, collector, and local roads respectively. The highest speed was observed for commute trips, in morning peak hours, in air temperature in the range of 10-20oC. The impact of road grade on bicycle speed was also analyzed (Clarry, Faghih Imani and Miller, 2019; Castro, Johansson and Olstam, 2022). Based on results presented by (Parkin and Rotheram, 2010) on flat mean bicycle speed is 21.6km/h. For every additional 1% of downhill gradient, it increases by 0.86km/h, and for every additional 1% of uphill gradient it reduces by 1.4km/h. In (Toljic, Brezina and Emberger, 2021), it was shown that the roughness of a road surface does not have significant impact on cyclists' velocity choices.

Bicycle speed models presented in (Strauss and Miranda-Moreno, 2017; Parkin and Rotheram, 2010) were characterized by relatively low coefficient of determination up to R2=0.246 and R2=0.266 respectively.

The traditional method of bicycle speed estimation is empirical measurement. Bicycle speed can be determined directly using speed radar or indirectly, as a quotient of measurement base length and travel time calculated using a stopwatch (Thompson et al., 1997; Bernardi and Rupi, 2015). Video technique is also commonly used. Based on recorded videos and with the use of additional software, not only a travel time along measurement base but also cyclist trajectory along road segments or intersections can be determined (Ling and Wu, 2004; Zaki, Sayed and Cheung, 2013). In recent years, bicycle speed was also estimated using GPS data. Bicycle GPS data from units installed on bikes are generally obtained from a limited number of cyclists (a few or a dozen) (El-Geneidy, Krizek and Iacono, 2007; Parkin and Rotheram, 2010; Cubells, Miralles-Guasch and Marquet, 2023; Yaqoob et al., 2023). Sample size can be significantly increased by using GPS data from the mobile app. For example in (Strauss and Miranda-Moreno, 2017) and (Saunier and Chabin, 2020) data collected during over 10 000 trips and almost 78 000 trips was used respectively. Another source of bicycle GPS data are bikesharing systems, which are implemented in more and more cities around the world. Bikesharing system data was used in comparision of travel behavior of short-term users and annual members of the system (Buck et al., 2013), evaluation of impact of land use on bicycle traffic volume (Imani et al., 2014), evaluation of bicyclist's perception of roadway environment, safety and comfort (Joo et al., 2015; Fishman and Schepers, 2016), analysis of the share of public bikes in daily bicycles traffic volume (Pogodzinska, Kiec and D'Agostino, 2020) and impact of type and standard of bicycle infrastructure on public bicycle traffic volume (Brown, Scott and Páez, 2022), assessment of the attractiveness of bicycle infrastructure (Krukowicz et al., 2021), analysis of the impact of bikesharing system on health of its users (Woodcock et al., 2014). The review of bikesharing system studies is provided in (Zhou et al., 2022). The number of trips made by public bicycles depends on the size of the city, the number and type of public bicycles (electric or not), location of rental stations, characteristics of other modes of transport (e.g. parking fees), etc. In Krakow (Poland), from March 2017 to December 2019 public bikes were rented over 2.5mln times.

The main concern when using GPS data in the analysis is its accuracy. Depending on weather conditions, the presence of high buildings or tunnels next

to analyzed locations, registered coordinates of bicycle, and a as consequence, bicycle speed may differ from the real ones. The most popular method of GPS data filtering is a Kalman filter (Kalman, 1960). The description and implementation of other signal filtering approaches in bicycle safety analysis can be found in (Murgano et al., 2021) and (Yaqoob et al., 2023).
Irrespective of the source of bicycle GPS data, when estimating bicycle speed relationship between the speed of all cyclists and the group of cyclists from whom GPS data was collected has to be determined. Based on results presented in (Allen et al., 1998; Jensen et al., 2010; Fishman and Schepers, 2016) speeds of bikesharing system users are lower than speeds achieved by regular cyclists. However, that conclusion was made based on research data in different locations. The authors do not know of any research where the speed of regular cyclists, bikesharing system users, and mobile apps users were compared for the same research sites.

## 3. Data collection

The research was made in reference to 18 locations different in terms of the type of bicycle infrastructure (bicycle path, shared pedestrian and bicycle path, contraflow lane) separately for road segments and bicycle crossings (with and without traffic signals). Research sites were selected in locations with relatively high bicycle traffic volume. Traffic management and land use next to selected locations, which can influence cyclists' speed did not change significantly in the last few years. Research sites are listed in Table 1 and their location is presented in Figure 1.

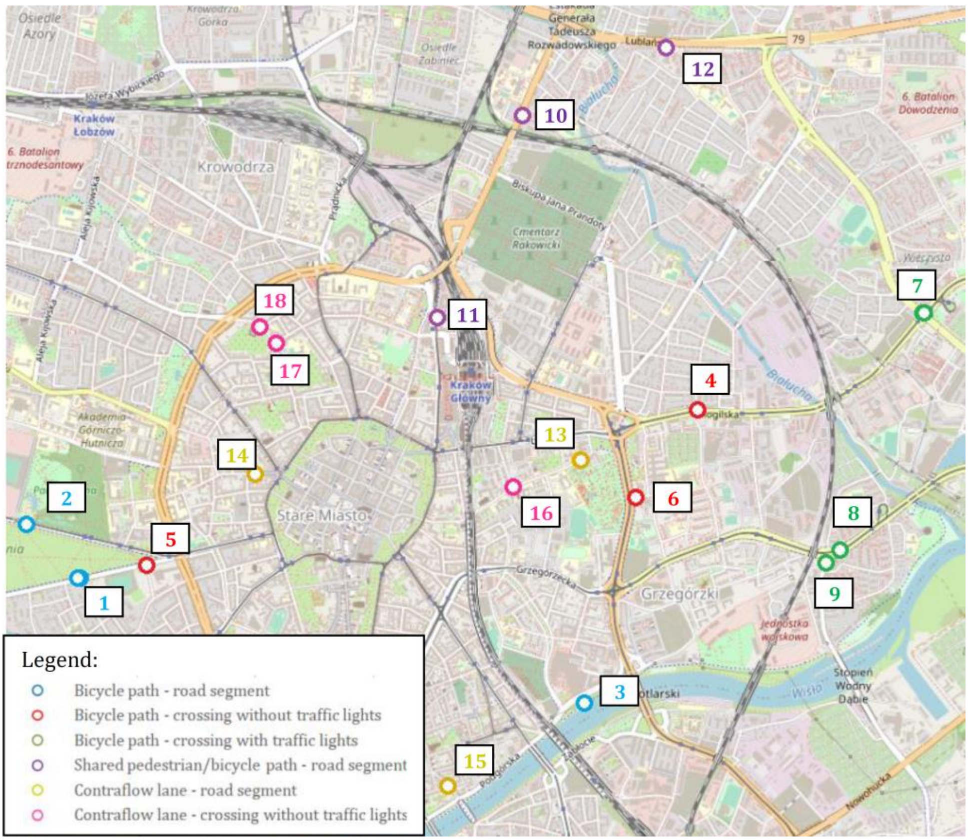


Fig. 1. Location of research sites (based on OpenStreetMap)

### 3.1. Empirical measurements

Empirical measurements of bicycle speed were conducted in the month of May, June or July in 2017, 2018, 2019, and 2021 during good weather conditions (no rainfall) and in daylight. The video technique was used. High-resolution cameras were installed on steel masts 4-6m high and placed near analyzed locations. Measurement at each site lasted around 2 hours. By using VSDC Free Video Editor virtual cross sections creating measurement base were added to each registered video. When road segments were analyzed, cross sections were preliminarily marked along the segment during empirical measurements (e.g. by traffic cones). It helped to mark sections in known distance to each other. Cross sections were placed at a distance about 10m along segment 40-50m. When bicycle crossings were analyzed, cross sections were marked at the beginning and the end of the crossing. An example of a camera view with marked cross sections is presented in Figure 2. Recorded videos were then analyzed using own software called KBDiIR Player. It allows to play video in 3 different shots, at various speeds and view zoom. Videos were played 4 times slower. A moment when the cyclist arrived at each virtual cross section was detected by pressing the dedicated keyboard button (each cross section had own dedicated button). As a result, txt file including the code of the cross section and the time when the cyclist arrived at that section was created. Bicycle speed was calculated as a quotient of measurement base (measured in-situ) and travel time was calculated based on timestamps in which cyclists were detected in marked cross sections. The research focused on free-flow speed, and therefore only the speeds of cyclists who did not stop in the analyzed locations were measured.

### 3.2. Bicycle GPS data

In the research two GPS data sources were analyzed: bikesharing system (Wavelo) and Strava mobile app, which are described below.

a) Bikesharing system data

Bikesharing system in Krakow called Wavelo operated from 2008 to the end of 2019. At the end of 2019, it consisted of 169 stations and around 1500 bikes. Detailed Wavelo GPS data was shared by Cracow Road Administration. Because of the great amount of data collected by the system, data was gathered only for 1 month i.e. June 2017. The month of June was selected due to good weather conditions and high bicycle volumes at that time. The database consisted of almost 150 000 trips and over 2mln GPS points. No personal data of bikesharing system users' was given.

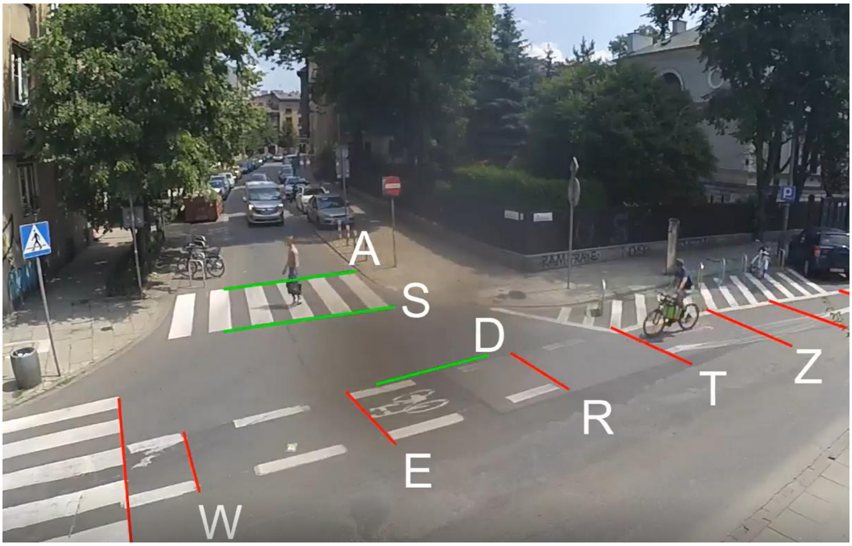



Fig. 2. Camera view with added cross sections

b) Strava data

Strava mobile app is dedicated to runners and cyclists who would like to record the parameters of their activities. It allows monitoring time, route, speed of the trip, and comparison of own results with the results of other app users. GPS data can be downloaded from the Strava website for specified road segments. To do so, firstly road segments with selected research sites along it were searched. All trips recorded on the segments were then downloaded. The database included the gender of the cyclists and he’s or she’s age as one of the six determined ranges. Because this data was not available in the Wavelo database, the impact of cyclists’ gender and age on the speed was not analyzed in the paper. In total, GPS data for around 45 000 trips, taken in the period 2017-2021 (the same as for empirical measurements, was collected.

GPS data for both sources was available in gpx format. Figure 3 presents the extract of available data. Each bicycle trip was a sequence of GPS points described by coordinates (latitude and longitude) and timestamps. In general, the time and coordinates were given with an accuracy of 1 second.

Based on the information given by the provider of bike share technology to the Wavelo system (Social Bicycles company), coordinates were registered with 1Hz frequency in case of a significant change of bicycle trajectory or speed, when acceleration or deceleration was higher than a threshold value (unfortunately, the threshold was not revealed). According to (Murgano et al., 2021) 1Hz frequency is a minimum to provide suitable speed profiles. If none of the situations mentioned above took place (smooth bicycle ride), to limit the amount of collected data, coordinates were registered with higher intervals (mainly 5s, sometimes 10s), which can be seen in the sample of data presented in Figure 3.


```
<trk>
 <trkseg>
  <trkpt lat="50.06317333333333" lon="19.933743333333332">
   <time>2017-05-31T22:03:41Z</time>
  </trkpt>
  <trkpt lat="50.06317333333333" lon="19.933743333333332">
   <time>2017-05-31T22:04:01Z</time>
  </trkpt>
  <trkpt lat="50.06323166666667" lon="19.933571666666666">
   <time>2017-05-31T22:04:11Z</time>
  </trkpt>
  <trkpt lat="50.063253333333336" lon="19.933521666666667">
   <time>2017-05-31T22:04:16Z</time>
  </trkpt>
  <trkpt lat="50.06327" lon="19.933478333333333">
   <time>2017-05-31T22:04:26Z</time>
  </trkpt>
  <trkpt lat="50.06321333333333" lon="19.933578333333333">
   <time>2017-05-31T22:04:31Z</time>
  </trkpt>
  <trkpt lat="50.06313333333333" lon="19.933685">
   <time>2017-05-31T22:04:36Z</time>
```


Fig. 3. Extract GPS database.

Bicycle speeds were calculated by using a specially developed computer app. Firstly, GPS coordinates of tree zones "before", "on" and "after" analyzed research site had to be determined. When the road section was analyzed, three zones were evenly distributed along a 100m section. For bicycle crossing, zone "on" covered crossing, and zones "before" and "after" – road section about 50m long at the approach to the crossing from both sides.

The mean bicycle speed between two GPS points was calculated as a quotient of the distance between two consecutive points and the difference of timestamps for those points (Equation 1). The distance was calculated based on GPS coordinates taking into account the spherical shape of the Earth (Equation 2).

$$v_{i+1} = \frac{d_{i,i+1}}{t_{i+1} - t_i}\ [m/s] \quad (1)$$

$$d_{i,i+1} = \{acos[sin(Lat_i) \cdot sin(Lat_{i+1})] + \cos(Lat_i) \cdot \cos(Lat_{i+1}) \cdot \cos(Lon_i - Lon_{i+1})\} \cdot 6371000\ [m \quad (2)$$

where: $d_{i,i+1}$ – distance between *i* and *i+1* GPS points [m]; $Lat_i$, $Lat_{i+1}$ – latitude of *i* and *i+1* point [-]; $Lon_i$, $Lon_{i+1}$ – longitude of *i* and *i+1* point [-]; $t_i$, $t_{i+1}$ – timestamps for i and i+1 point [s]; vi+1 – bicycle speed in between points *i* and *i+1* [m/s].

Linear interpolation was used to calculate cyclists' speed every 1s along three zones (Figure 4). The speed of each cyclist was calculated as a mean speed for points in all three zones (for road segments) or only in the "on" zone (for crossings). Finally, the mean bicycle speed in each location was calculated as a mean for all cyclists. Tree zones were used in the analysis for more accurate estimation of bicycle speed especially for bicycle crossings where zone "on" had limited distance and only 1 point or even none could be found within. In the paper, only speeds in the range of 1.4-15m/s were included in the analysis. Speed 1.4m/s is a pedestrian speed in Polish design guidelines, and a speed over 15m/s was difficult to achieve for bikeshare system users and could be a result of GPS disruptions.

The research focused on free-flow speed. It should be mentioned that when using only historical GPS data, it is impossible to determine if the calculated bicycle speed was in free flow or if it was influenced by e.g. the presence of other road users. Therefore, the free flow speed condition for the GPS data was based only on the speed interval mentioned above.

The main concern when using GPS data in the analysis is its accuracy. The most popular method of GPS data filtering, which is the Kalman filter, is difficult to use when analyzing bicycle traffic. Cyclists may change the trajectory of their trip when passing pedestrians or overtaking other cyclists. As a result, filtered position of a bike may not reflect the real cyclist's behavior. Moreover, the given GPS data included only coordinates and time stamps data, there was no more data from NMEA string available, which could improve the reliability of the data. Therefore, in the paper filtering of GPS data was limited to exclusion from the analysis of bicycle speeds higher than 15m/s.

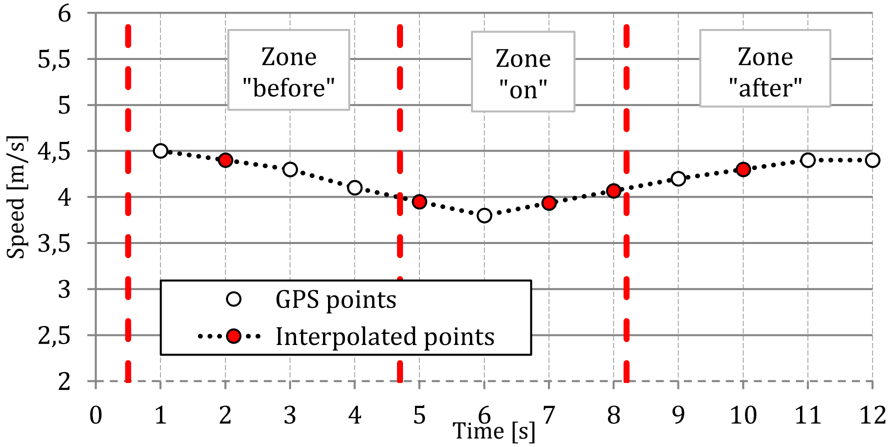



Fig. 4. Bicycle free flow speed calculation using computer app

## 4. Methodology

The aim of the paper was to determine if bicycle speeds calculated based on the GPS source (bikesharing system or Strava) are statistically significantly different from speeds gathered in empirical measurement. If so, the relationship between those speeds was evaluated.

To assess the statistically significant difference in bicycle speeds two-tails test for two means were conducted. The null hypothesis states that there is no difference between compared means (m1=m2). Because in all cases sample sizes were no less than 31, test statistic was calculated based on Equation 3.

$$u = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2}}} \ [-] \quad (3)$$

where: u – test statistics [-]; $n_1$, $n_2$ – samples' sizes [-]; $s_1$, $s_2$ – standard deviation in two samples; $\bar{x}_1, \bar{x}_2$ – mean value of the random variable for two samples.

Two linear regression models with observed bicycle speed as a dependent variable and bicycle speed from one of the GPS sources as an independent variable were developed (Equation 4). Despite of the fact that each homogenous group of locations (based on the type of bicycle infrastructure and element of the road network (road sections, bicycle crossing)) consisted from only 3 locations, the impact of quantitative variables (bicycle and road infrastructure) was tasted. Calculations were made in IBM SPSS Statistics 20. The parameters of the models were estimated using the maximum likelihood method.

$$V_{observed} = \alpha + \beta * V_{Wavelo/Strava} + \gamma_i * Z_i \ [m/s] \quad (4)$$

where: $V_{observed}$ – mean observed bicycle speed [m/s]; α –intercept [-]; $V_{Wavelo/Strava}$ – mean Wavelo or Strava bicycle speed [m/s]; β – regression coefficient for speed calculated based on GPS data [-]; $Z_i$ – quantitative variables (type of bicycle infrastructure *T*, element of road network *E*); $\gamma_i$ – regression coefficient for quantitative variables [-].

In equation 4 two quantitative variables $Z_i$ were analyzed:

- type of bicycle infrastructure *T*, where each type of bicycle facility (bicycle path, shared pedestrian/bicycle path, and contraflow lane) was analyzed separately;
- element of road network *E*, where each element (road section, bicycle crossing with traffic signals, and bicycle crossing without traffic signals) was analyzed separately, and additionally, bicycle crossing with and without traffic signals were analyzed together.

## 5. Results

The mean bicycle speed for each data source and research location are presented in Table 1. Table N is a sample size [B]; $V_{observed,}$ $V_{Wavelo}$, $V_{Strava}$ are mean bicycle speeds from empirical measurements, Wavelo and Strava respectively [m/s]; SD is a standard deviation of mean speed [m/s]; Wz is a coefficient of variation of mean speed [-]; $V_{min}$ and $V_{max}$ are respectively minimum and maximum values of speed [m/s]; V15, V50, and V85 are respectively 0.15, 0.50 and 0.85 quantiles of speed [m/s]; $N_{min}$ is a minimum samples size calculated assuming 5% error in estimating mean speed and a 0.95 confidence level [$B_{min}$]. For all three data sources sample sizes were higher than the minimum sample sizes needed.

The mean observed speed of regular cyclists was in the range of 2.7-6.17m/s (9.72-22.21km/h). The results are comparable with those presented in (Allen et al., 1998). In general, cyclists achieved the highest speeds on bicycle paths (4.65m/s (SD=0.92m/s), 5.18m/s (SD=1.67m/s), 6.88m/s (SD=1.49m/s) for Wavelo users, regular cyclists and Strava users respectively), lower on shared pedestrian/bicycle paths (4.41m/s (SD=0.82m/s), 5.17m/s (SD=1.16m/s), 6.27m/s (SD=1.46m/s) for Wavelo users, regular cyclists and Strava users respectively), and the lowest on contraflow lanes (3.92m/s (SD=0.69m/s), 4.44m/s (SD=1.07m/s), 5.94m/s (SD=1.46m/s) for Wavelo users, regular cyclists and Strava users respectively).

The speed of cyclists riding along bicycle paths was higher than at bicycle crossings. For bicycle crossing without traffic signals, the speed was lower by 0.77m/s for Wavelo users and regular cyclists and 1.55m/s for Strava users. Reduction of bicycle speed on bicycle crossing with traffic signals speed was 2 times higher than on crossing without traffic signals (1.79m/s, 1.40m/s, 2.69m/s for Wavelo users, regular cyclists, and Strava users respectively). For contraflow lanes and all data sources, it was found that bicycle speeds on crossings were higher than on road segments by 0.25-0.94m/s. It may be a result of the fact, that cyclists have the right of way and want to leave a conflict zone as soon as possible.

The results of two-tails test for two means are shown in Table 2. For 16 out of 18 analyzed locations, Wavelo speeds were statistically significantly lower by 0.28-1.76m/s with a mean of 0.86m/s (17.4%) than mean bicycle speeds from empirical measurements ($p \leq 0.01$). The results are comparable with (Fishman and Schepers, 2016) where bikeshare system users' speeds were found to be 5-10km/h (1.4-2.8m/s) lower than the speeds of regular cyclists. For two locations Wavelo speeds were higher than speeds from empirical measurement, however, no explanation can be made based on gathered data.

Table. 1. The performances of different trajectory prediction models

| No. | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research site | | Focha | Al. 3 Maja | Bulwary Wiślane | Grunwaldzka | Kasztelańska | Sądowa | Meissnera | Al. Pokoju | Ofiar Dąbia | 29 Listopada | Pawia | Opolska | Kopernika | Krupnicza | Mostowa | Kopernika | Łobzowska | Teresy |
| Bicycle facility | | Bicycle path | | | | | | | | | Shared pedestrian/ bicycle path | | | Contraflow lane | | | | | |
| Road infrastructure | | Road section | | | Bicycle crossing without traffic signals | | | Bicycle crossing with traffic signals | | | Road section | | | Road section | | | Bicycle crossing without traffic signals | | |
| **Empirical** | N | 248 | 138 | 338 | 251 | 110 | 138 | 59 | 31 | 47 | 129 | 90 | 100 | 156 | 94 | 98 | 89 | 63 | 134 |
| | $V_{mean}$ | 4.7 | 6 | 4.8 | 6.2 | 2.7 | 4.4 | 4.6 | 3.9 | 2.9 | 5.2 | 5 | 5.3 | 4.6 | 4.3 | 4.4 | 6 | 5 | 5.2 |
| | SD | 1.51 | 1.65 | 1.85 | 1.73 | 0.71 | 1.22 | 0.83 | 0.53 | 0.49 | 1.03 | 1.17 | 1.29 | 1.11 | 1.01 | 1.08 | 1.28 | 0.96 | 1.4 |
| | Wz | 0.32 | 0.27 | 0.38 | 0.28 | 0.26 | 0.28 | 0.18 | 0.14 | 0.17 | 0.2 | 0.23 | 0.24 | 0.24 | 0.23 | 0.24 | 0.21 | 0.19 | 0.27 |
| | Vmin | 2.1 | 2.4 | 1.6 | 3 | 1.5 | 1.5 | 2.9 | 2.7 | 1.8 | 2.2 | 3.1 | 2.7 | 2 | 2.7 | 2.1 | 3.9 | 3.1 | 1.4 |
| | Vmax | 11.8 | 10.9 | 14.3 | 14.1 | 4.3 | 6.7 | 6.3 | 5 | 4 | 9.2 | 8 | 10 | 8 | 8 | 8 | 11.2 | 8.3 | 10.2 |
| | V15 | 3.4 | 4.5 | 3.3 | 4.5 | 2 | 3 | 3.7 | 3.4 | 2.4 | 4.3 | 3.7 | 3.8 | 3.5 | 3 | 3.3 | 4.9 | 4.1 | 4 |
| | V50 | 4.4 | 5.7 | 4.4 | 5.9 | 2.6 | 4.3 | 4.6 | 3.8 | 2.9 | 5.3 | 5 | 4.9 | 4.5 | 4.2 | 4.3 | 5.8 | 4.9 | 4.9 |
| | V85 | 6 | 7.6 | 6.4 | 7.8 | 3.5 | 5.8 | 5.5 | 4.3 | 3.4 | 6.2 | 6.7 | 6.3 | 5.6 | 5.6 | 5.6 | 7.5 | 5.7 | 6.5 |
| | Nmin | 158 | 114 | 226 | 121 | 105 | 120 | 51 | 28 | 44 | 60 | 84 | 90 | 89 | 84 | 92 | 69 | 57 | 113 |
| **Wavelo** | N | 310 | 619 | 115 | 1736 | 633 | 352 | 2250 | 187 | 147 | 1049 | 335 | 1211 | 391 | 144 | 722 | 250 | 178 | 36 |
| | $V_{Wavelo}$ | 4.8 | 5.2 | 4 | 4.5 | 3.1 | 4 | 3.1 | 3.1 | 2.4 | 4.6 | 4.3 | 4.4 | 4 | 4 | 3.7 | 4.3 | 4.3 | 4.1 |
| | SD | 0.91 | 0.96 | 0.9 | 0.96 | 0.59 | 1.02 | 0.92 | 0.73 | 0.63 | 0.93 | 0.74 | 0.8 | 0.61 | 0.68 | 0.77 | 0.78 | 0.88 | 0.59 |
| | Wz | 0.19 | 0.19 | 0.22 | 0.21 | 0.19 | 0.26 | 0.3 | 0.23 | 0.27 | 0.2 | 0.17 | 0.18 | 0.15 | 0.17 | 0.21 | 0.18 | 0.2 | 0.14 |
| | Vmin | 2.2 | 1.7 | 2 | 1.5 | 1.8 | 1.4 | 1.4 | 1.5 | 1.4 | 1.9 | 1.9 | 2.1 | 2 | 1.6 | 1.2 | 1.9 | 1.5 | 2.8 |
| | Vmax | 8.5 | 8 | 7.7 | 8.5 | 5.8 | 7.3 | 7.1 | 5 | 3.8 | 7.6 | 6.2 | 7.7 | 5.6 | 5.4 | 5.7 | 6.2 | 6.5 | 5.2 |
| | V15 | 4 | 4.1 | 3.3 | 3.6 | 2.5 | 3 | 2.2 | 2.3 | 1.7 | 3.6 | 3.5 | 3.6 | 3.5 | 3.3 | 2.8 | 3.4 | 3.5 | 3.5 |
| | V50 | 4.7 | 5.2 | 3.8 | 4.5 | 3.1 | 3.8 | 2.9 | 3.2 | 2.3 | 4.5 | 4.3 | 4.3 | 4 | 4 | 3.6 | 4.3 | 4.4 | 4.2 |
| | V85 | 5.5 | 6.1 | 4.9 | 5.5 | 3.7 | 5.1 | 4.1 | 3.8 | 3.1 | 5.6 | 5 | 0 | 4.7 | 4.7 | 4.6 | 5.1 | 5.2 | 4.7 |
| | Nmin | 56 | 53 | 76 | 69 | 55 | 102 | 136 | 84 | 109 | 63 | 47 | 51 | 35 | 45 | 66 | 52 | 63 | 32 |
| **Strava** | N | 1540 | 989 | 505 | 3202 | 1484 | 1999 | 2085 | 433 | 151 | 600 | 150 | 419 | 377 | 105 | 166 | 359 | 215 | 88 |
| | $V_{Strava}$ | 7.6 | 7.3 | 5.7 | 6.6 | 3.1 | 6.3 | 4.8 | 4.4 | 3.3 | 6.7 | 5.4 | 6.7 | 6.2 | 6.7 | 4.9 | 6.2 | 6.2 | 6.2 |
| | SD | 1.57 | 1.55 | 1.34 | 1.72 | 1.08 | 1.76 | 2.12 | 2.22 | 1.03 | 1.51 | 1.41 | 1.47 | 1.31 | 1.63 | 1.43 | 1.29 | 1.5 | 1.19 |
| | Wz | 0.21 | 0.21 | 0.23 | 0.26 | 0.35 | 0.28 | 0.44 | 0.5 | 0.31 | 0.23 | 0.26 | 0.22 | 0.21 | 0.24 | 0.29 | 0.21 | 0.24 | 0.19 |
| | Vmin | 2.2 | 2.3 | 1.8 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.6 | 1.9 | 1.4 | 2 | 1.8 | 2.3 | 1.6 | 1.5 | 1.9 | 3.1 |
| | Vmax | 15 | 12 | 9.1 | 13.3 | 11.8 | 14.7 | 12.4 | 13.9 | 5.3 | 12.7 | 9.6 | 11.5 | 10.6 | 14.6 | 14.2 | 10.9 | 12.1 | 9.5 |
| | V15 | 6.1 | 5.9 | 4.1 | 4.8 | 2 | 4.6 | 2.5 | 2 | 2 | 5.2 | 3.8 | 5.3 | 5.2 | 5.1 | 3.4 | 4.9 | 4.7 | 5 |
| | V50 | 7.6 | 7.3 | 5.8 | 6.6 | 3 | 6.3 | 4.7 | 4.1 | 3.3 | 6.6 | 5.6 | 6.7 | 6.2 | 6.6 | 4.8 | 6.3 | 6.4 | 6.2 |
| | V85 | 9.3 | 8.7 | 7.1 | 8.3 | 4.2 | 7.9 | 6.9 | 6.9 | 4.5 | 8.1 | 6.7 | 8.3 | 7.4 | 8.3 | 6.4 | 7.4 | 7.5 | 7.4 |
| | Nmin | 65 | 70 | 85 | 106 | 183 | 119 | 298 | 382 | 148 | 78 | 105 | 73 | 67 | 92 | 131 | 66 | 89 | 58 |

Table 2. Results of two-tailed test for two means

| No. | Name of research site | Bicycle facility | Road infrastructure | Compared to Wavelo | | Compared to Strava | |
|---|---|---|---|---|---|---|---|
| | | | | u | p-value | u | p-value |
| 1 | Focha | Bicycle path | Road section | -1.053* | 0.294 | 35.483 | <0.001 |
| 2 | Al. 3 Maja | | | 6.883 | <0.001 | 11.434 | <0.001 |
| 3 | Bulwary Wiślane | | | 6.937 | <0.001 | 10.566 | <0.001 |
| 4 | Grunwaldzka | | Bicycle crossing without traffic signals | 19.702 | <0.001 | 4.717 | <0.001 |
| 5 | Kasztelańska | | | -4.654* | <0.001 | 4.832 | <0.001 |
| 6 | Sądowa | | | 3.692 | <0.001 | 19.648 | <0.001 |
| 7 | Meissnera | | Bicycle crossing with traffic signals | 12.467 | <0.001 | 1.660 | 0.097 |
| 8 | Al. Pokoju | | | 5.520 | <0.001 | 3.648 | <0.001 |
| 9 | Ofiar Dąbia | | | 4.122 | <0.001 | 3.311 | 0.001 |
| 10 | Al. 29 Listopada | Shared pedestrian/bicycle path | Road section | 6.370 | <0.001 | 15.362 | <0.001 |
| 11 | Pawia | | | 5.676 | <0.001 | 2.987 | 0.003 |
| 12 | Opolska | | | 7.729 | <0.001 | 11.504 | <0.001 |
| 13 | Kopernika | Contraflow lane | Road section | 6.442 | <0.001 | 17.121 | <0.001 |
| 14 | Krupnicza | | | 2.412 | 0.016 | 18.289 | <0.001 |
| 15 | Mostowa | | | 6.367 | <0.001 | 3.996 | <0.001 |
| 16 | Kopernika | | Bicycle crossing without traffic signals | 12.850 | <0.001 | 1.554 | 0.121 |
| 17 | Łobzowska | | | 4.927 | <0.001 | 8.631 | <0.001 |
| 18 | Teresy | | | 6.715 | <0.001 | 7.636 | <0.001 |

where: (*) - a negative value of test statistic u means that the mean Wavelo speed was higher than the mean observed speed (calculated based on empirical measurement).

For all analyzed locations, speeds of Strava users were by 0.18-2.95m/s with a mean of 1.07m/s (23.1%) higher than speeds from empirical measurements. Those differences were statistically significant for 16 out of 18 locations ($p \leqslant 0.01$).

The standard deviation of mean bicycle speed was in the range of 0.49-2.22m/s, which is similar to values presented in previous research (Thompson et al., 1997; Bernardi and Rupi, 2015). In general, the standard deviation of the speed of Strava users was the highest (in the range of 1.03-2.22m/s with a mean of 1.51m/s), lower for regular cyclists (in the range of 0.49-1.85m/s with a mean of 1.16m/s), and the lowest for Wavelo users (in range 0.59-1.02m/s with a mean 0.80m/s).

General forms of developed linear regression models are presented in Equations 5 and 6 for Wavelo and Strava data respectively. Model for Wavelo was developed excluding data from locations 1 and 5, where Wavelo speeds were higher than speeds gathered during empirical measurements. The parameters of the models are presented in Table 3. The type of bicycle infrastructure had no statistically significant impact on analyzed relationships ($p>0.05$). The element of the road network (road section or bicycle crossing) was a statistically significant variable only in the Wavelo model. Additionally, the intercept was not statistically significant in this model ($p=0.717$).

$$V_{observed} = \beta_{Wavelo} * V_{Wavelo} + \gamma * E \;\; [m/s] \quad (5)$$

$$V_{observed} = \alpha + \beta_{Strava} * V_{Strava} \; [m/s] \quad (6)$$

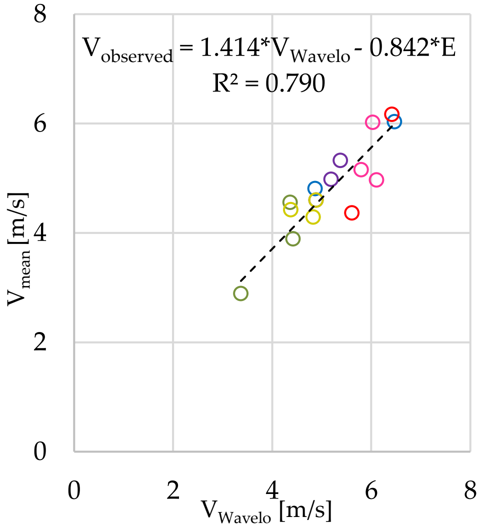
where: E – E=1 for road section, E=0 for bicycle crossing.

Table 3. Regression coefficients for the model developed for Wavelo (R2 = 0.790) and Strava (R2 = 0.604)

| Parameter | | Value | Standard error | p-value | 95% confidence interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| **Wavelo model** | | | | | | |
| $V_{Wavelo}$ | $\beta_{Wavelo}$ | 1.414 | 0.236 | <0.001 | 0.953 | 1.876 |
| E | $\gamma$ | -0.842 | 0.401 | 0.036 | -1.628 | -0.056 |
| **Strava model** | | | | | | |
| Intercept | $\alpha$ | 1.357 | 0.645 | 0.036 | 0.092 | 2.621 |
| $V_{Strava}$ | $\beta_{Strava}$ | 0.583 | 0.109 | <0.001 | 0.369 | 0.796 |

Developed models for Wavelo and Strava are presented in Figures 5a and 5b respectively. The coefficients of determination for those models were 0.790 and 0.604 respectively. The variance of bicycle speed is in almost 80% described by the variance of Wavelo speed, and in 60% described by the variance of Strava speed.

(a)




(b)

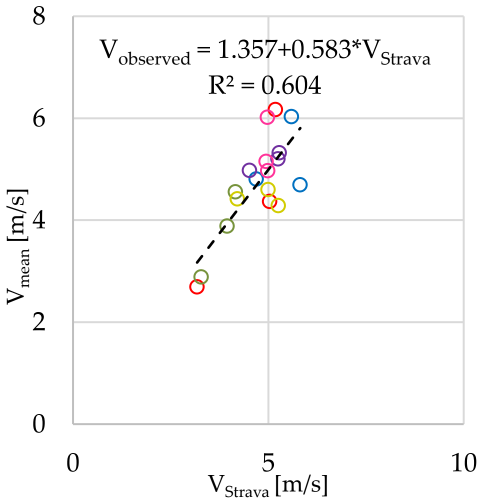



Fig. 5. Developed models a) for Wavelo and b) for Strava

## 6. Discussion and conclusions

The aim of the paper was to analyze relationships between the mean observed speed of regular cyclists and speeds obtain from two bicycle GPS data sources, i.e. bikeshare system and the Strava app. In total 18 research sites were selected different in terms of bicycle facility (bicycle path, shared pedestrian/bicycle path, contraflow lane) and element of road network (road segment, bicycle crossing). Results of two-tailed test for two means show that in general Wavelo speeds are statistically significantly lower and Strava speeds are statistically significantly higher than speed in empirical measurement by 17.4% and 23.1% respectively. Research results are in line with expectations. Wavelo bikes were heavier and had less gears (only 3) than regular bikes, therefore bikeshare system users' speeds were expected to be lower than the speeds of all cyclists. Strava users are mainly experienced bike riders, who achieve higher speeds than regular cyclists. In general, cyclists achieve the highest speeds on bicycle paths, lower on shared pedestrian/bicycle paths, and the lowest on contraflow lanes. Standard deviation of mean bicycle speed is the highest for Strava, lower for regular cyclists, and the lowest for Wavelo users. Presented models describing the relationship between regular cyclists' speed and speed calculated based on GPS data are characterized by relatively high values of coefficient of determination (R2=0.790 and R2=0.604 for Wavelo and Strava respectively). It suggests that bicycle free-flow speed can be estimated based on GPS data either from bikeshare system or a dedicated app.

It should be mentioned that the results presented in the paper should be analyzed considering also several limitations. The data used in the paper included only coordinates and time stamp data. Unfortunately, there was no speed data from the NMEA string available for more reliable speed evaluation. Due to the limited accuracy of GPS data, which depends on the weather conditions, and the presence of high buildings or tunnels next to analyzed locations, bicycle speeds calculated based on time and location could be biased. In the paper filtering of GPS data was only limited to exclusion from the analysis of bicycle speeds higher than 15m/s. No other filtering methods were used. According to (Murgano et al., 2021) GPS data must be collected with at least a 1 Hz frequency to provide suitable speed profiles. Available GPS data was characterized by that high

sampling frequency in case of a significant change of bicycle trajectory or speed. However, in other case (smooth bicycle ride), to limit the amount of collected data, coordinates were registered with higher intervals (mainly 5s, sometimes 10s). It was also impossible to determine if speed calculated based on Wavelo or Strava GPS data was in free-flow or if it was influenced by e.g. the presence of other road users or the operation of traffic signals. The presented results show lower speeds at signalized intersections when compared to no signalized ones, which may be a result of signal change when cyclists were approaching to the intersection.
Nevertheless, it should be noted that the results presented in the paper are important from a practical point of view. Cyclists' speed is an important variable in the planning, design, and operation of road infrastructure. However, it should be emphasized that collecting data on cyclist traffic, mainly speed, is time-consuming and difficult (due to the possibility for cyclists to use various elements of infrastructure for vehicles, pedestrians, and cyclists). Therefore, it is important to develop speed and volume estimation methods using new technologies such as GPS data. The relationships between various sources of GPS data and the regular cycling traffic presented in the paper allow for an estimation of the free-flow speed of cyclists, if any other and more accurate data are not available, or when bicycle speed is estimated for multiple locations. These results could be used to assess the efficiency of road infrastructure (levels of service) and road safety (for example speed differences between road users), as well as infrastructure design (e.g. inter-green times at an intersection with traffic signals).

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