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THE IMPACT OF WEATHER ON BICYCLE RISK EXPOSURE

Sylwia PAZDAN
Faculty of Civil Engineering, Cracow University of Technology, Krakow, Poland

Abstract:
Traffic volume is the main independent variable of risk exposure in road safety models. Cyclists as a vulnerable road users are more exposed to weather conditions than e.g. car drivers. As a result, their decision of whether to cycle is strongly related to weather conditions. It suggests that any change in the weather may have a significant effect on bicycle use. Objective of the paper was to indicate which weather parameters have a significant impact on bicycle use, how a change in weather parameters affects the change in bicycle volume (risk exposure) and, consequently, predicted number of crashes with cyclists and which factors differentiate the impact of weather conditions on bicycle volume. The impact of weather on bicycle volume variability was estimated based on literature review. The Web of Science, Scopus and TRID databases were searched. Finally, 33 papers from 1977 up to 2020, different in terms of the methodology used, country of origin, and analyzed group of cyclists, were reviewed. The impact of change in weather conditions on the predicted number of crashes with cyclists was estimated using own road safety models and previous research results. Results indicate that air temperature, precipitation, sunshine, cloud cover, humidity, and wind strength, have a significant influence on bicycle use. The impact of the weather on bicycle volume differs between different cyclists' groups (different levels of experience, age, gender), trip motivations (recreational, commuting, etc.) and locations (countries, cities, climate zones). The paper shows complexity of impact of weather conditions on cycling and sensitivity of relationship between weather conditions and bicycle volume (i.e. risk exposure) and, as a consequence, bicycle safety. Results indicate that weather conditions should always be taken into consideration when analyzing cycling, especially in road safety analysis. The discussion of presented research results, research methods used with their limitations, and recommendations for future research were described.

Keywords: *cycling, bicycle demand, weather, traffic volume variability, bicycle road safety.*

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Contact:
sylwia.pazdan@pk.edu.pl [*https://orcid.org/0000-0001-6106-7768]*

1. Introduction

The bicycle is a healthy, low-cost and environment-friendly mode of transportation. Individual features (e.g. income, gender, age), initiatives and policy of local authorities, presence and type of bicycle infrastructure, perceived risk of injury, and the presence of bikeshare systems are some of the many factors affecting bicycle volume. One of them is also the weather. Cycling is more sensitive to weather conditions compared with other modes of transportation (Sabir, 2011), (Miranda-Moreno and Nosal, 2011). More than half of cyclists (58%) consider the weather when deciding whether to bike (Gallop, Tse and Zhao, 2012). The daily fluctuation of bicycle volume in 80% is described by weather conditions (Thomas, Jaarsma and Tutert, 2013). It suggests that any change in the weather may have a significant effect on bicycle use.

Traffic volume is one of the main independent variables in road safety analysis (Gaca, 2002), (Li *et al.*, 2016). Research on impact of weather conditions on number of bicycle crashes or injuries was conducted previously (Kim *et al.*, 2007), (Klop and Khattak, 1999), (Prati *et al.*, 2017). However, those research did not include a change in cyclists' risk exposure in different weather conditions. That approach would give a more insightful estimation of the impact of weather on cyclists road safety. Aside from road safety analysis, bicycle volume data is required in infrastructure planning and designing (estimations of bicycle traffic distribution, calculations of traffic performance and traffic signals program, etc.). When planning or designing road infrastructure, traffic volume has to represent traffic conditions in a long-term period. Therefore, change in bicycle volume as a result of climate change should be taken into consideration. Additionally, estimation of bicycle volume variation due to change in weather conditions enables for a more appropriate comparison of bicycle volumes in different locations. It is necessary when the increase in cyclists volume is estimated. Therefore, knowledge of impact of weather conditions on bicycle volume is necessary in various bicycle traffic analysis.

The aim of the paper was to indicate which weather parameters have a significant impact on bicycle volume and how change in weather parameters can affect bicycle use (i.e. bicycle risk exposure) and, consequently, predicted number of crashes with cyclists. The impact of weather on bicycle volume variability was estimated based on literature review. The Web of Science, Scopus and TRID databases were searched. Finally, 30 papers from 1977 up to 2019, different in terms of the methodology used, country of origin, and analyzed group of cyclists, were in detail reviewed. The discussion of presented research results, research methods used to evaluate impact of weather on bicycle volume and their limitations were described. The impact of change in weather conditions on risk exposure and therefore predicted number of accidents involving cyclists was estimated using own road safety models and previous research results. The paper also includes recommendations for future research.

Presented results show complexity of impact of weather conditions on bicycle volume and sensitivity of this relationship. The paper is informative for road administration, designers and transport planners.

2. Impact of weather conditions on bicycle use

2.1. Literature review method

The impact of weather on bicycle volume variability was estimated based on literature review. A few databases were searched to gather research papers, i.e. Web of Science (WoS), Scopus and Transport Research International Documentation (TRID). The keywords used in searching were: "bicycle", "bicycle volume" combined with "weather" or "environment". Table 1 presents the number of hits for each used search term in different databases. The total number of found papers was 1150.

Table 1. The number of hits for used search terms in each database

Search terms	WoS	Scopus	TRID	Total
"bicycle" and "weather"	236	65	488	789
"bicycle", "volume" and "weather"	33	1	44	78
"bicycle", "volume" and "environment"	88	12	183	283
Sum	357	78	715	1150

The first step was papers filtering. A lot of them already included a brief literature review, which enabled backward snowballing. Only papers in English were considered. Reviewed papers were selected

based on their relevance to the research questions i.e.:
- which weather factors have a significant impact on bicycle volume?
- how do weather conditions affect bicycle volume (qualitative and quantitative impact)?
- which factors differentiate the impact of weather conditions on bicycle volume?

Due to different climate and transportation culture, impact of weather on cyclists volume may differ between different geographic areas (countries, cities) (Ashqar, Elhenawy and Rakha, 2019). Therefore, papers with a different country of origin were included. Finally, 33 papers from 1977 up to 2020 were reviewed in detail and described in the paper. They varied in terms of the methodology used (different methods of bicycle volume data gathering and analysis) and analyzed groups of cyclists (different level of experience, age, gender, etc.). Figure 1 shows the distribution of reviewed papers published in successive years.

2.2. Summary and discussion of previous research results

Research results on impact of weather conditions on bicycle use are presented in details separately for survey (Table 2) and empirical research (Table 3) of bicycle volume gathering. In tables detailed information about source of data, year of publication, country of origin, method of bicycle volume gathering and data analysis, and research results are presented. For some papers in Table 2 additional notes are provided, which help understand how impact of weather on cyclists was evaluated. In subsubsections from 2.2.1 to 2.2.5 summary and discussion of presented research results are provided.

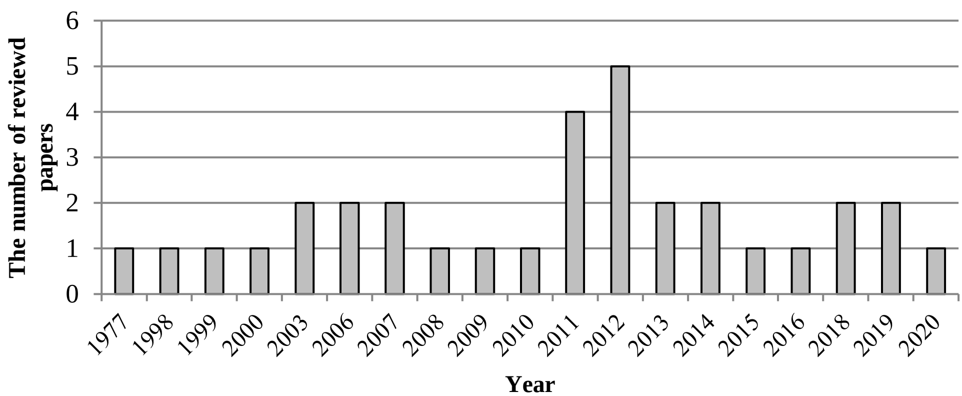

Fig. 1. The number of reviewed papers published in each year

Table 2. Results of survey research on impact of weather on bicycle use

Source	Method of bicycle use data gathering	Method of data analysis	Results	Country of origin
Nankervis, 1999	questionnaire survey among students, daily counts of number of parked bikes	descriptive statistics, correlation analysis, Pearson correlation	wind, rain and air temperature had a significant impact on daily bicycle volume; questionnaire survey showed that heavy rain is the biggest deterrent from bike riding (around 67% of respondents said they were deterred from bike riding in heavy rain, and 90% of them indicated that they still made the trip but used an alternative mode of transportation)	Australia
Richardson, 2000	household travel survey (19 686 people who made 74 056 trip in total)	descriptive statistics, regression analysis	compared to days with no rain, daily rainfall of around 8mm resulted in a 50% decrease in bicycle volume; differences between impact on weather on utilitarian and recreational cyclists were noticed; ideal temperature for bicycle riding was found to be 25°C	

Ahmed, Rose and Jacob, 2013	questionnaire survey among 738 commuting cyclists	descriptive statistics, binary logistic regression model	weather had different impact on casual cyclists (riding up to 3 days per week) and committed cyclists (riding at least 3 days per week); females were more sensitive to weather conditions than males; about 70% of casual cyclists and only 30% of commuting cyclists confirmed that weather influence their riding decisions; about 90% of casual cyclists and 50% of commuting cyclists changed day of bike riding as a result of the weather; more commuting cyclists (about 42%) changed their departure time as a results of weather than casual cyclists (about 38%); weather had comparable impact on both groups of cyclists in their route change decision (almost 20% of cyclists changed their route as a results of weather)	Australia
Brandenburg, Matzarakis and Arnberger, 2007	questionnaire survey (on-site interviews of trip motivation), long-term video monitoring (cycling patterns), temporally selective manual counting	human-biometeorological evaluation methodology, multiple linear regression models, descriptive statistics	commuting cyclists were less sensitive to weather conditions than recreational cyclists; during rainfall about 10% more commuting cyclists than recreational cyclists were observed; compared to no rainfall, when it was raining bicycle volume decreased by about 24% and 50% for commuting and recreational cyclists respectively; relationship between air temperature and recreational cyclists was stronger than with commuting cyclists (R^2 =0.71 and 0.52 respectively); in temperature below 18°C more commuting than recreational trips were made	Austria
Kienteka *et al.*, 2018	household survey among 677 adults	frequency distribution	respondents were asked to reported presence of some barriers that could hinder cycling; barriers included in the questionnaire were eg. bad weather, heavy traffic, fear of accidents, lack of safety, poor quality of streets, lack of bicycle lanes, distance to destinations. “Bad weather” was the most reported barrier for both leisure and commenting bike trips (reported by around 2/3 of all respondents)	Brazil
Winters *et al.*, 2006	nationwide household interview survey in 53 cities	multilevel multiple logistic regression models, descriptive statistics	*asked question: “In a typical week, how much time did you usually spend bicycling to work or to school or while doing errands?”* 30 days more with precipitations and freezing temperatures in a year resulted in less time spend on cycling for utilitarian purposes by 16% and 9% respectively; average summer maximum temperature and average wind speed did not have impact on bicycle use	Canada
Winters *et al.*, 2011	questionnaire survey among 1402 cyclists	exploratory factor analysis, descriptive statistics	*cyclists were asked to rate several factors (e.g. risk of injury in car-bike collision, possibility to make the trip in daylight hours, beautiful scenery of the route) in terms of its influence on their likely to cycle; score -1 meant much less likely to cycle, score -0.5 – less likely to cycle; score 0 – no influence on the decision to cycle; score 0.5 – more likely to cycle, score 1 – much more likely to cycle* total score for hot and humid weather -0.16, raining -0.63, icy or snowy route -0.86, daylight hours 0.50; regular cyclists were less sensitive to weather conditions than other groups of cyclists (occasional, frequent, potential cyclists)	
Saneinejad, Roorda and Kennedy, 2012	trip diary survey of approximately 5% of Toronto residents	multinomial logit model	younger cyclists and females were more sensitive to low temperatures than older cyclists and males; average daily bicycle trip rate was 1.682, 1.710, 1.717, 1.721, 1.731 and 1.721 work trips/person for temperatures below 0°C, the temperature in the range 1-5°C, 6-10°C, 11-15°C, 16-20°C and above 20°C respectively; daily trip rates decreased by 0.469 and 0.884 work trips/person for shower conditions and rain conditions respectively; for clear/cloudy conditions daily trip rate was 1.825 work trips/person	
Meng *et al.*, 2016	questionnaire survey among 553 cyclists	binary logistic regression model	cyclists prefer no rainfall in the past 60 minutes and relatively lower humidity (52.3%–62.7%), rainfall higher than 0.28 mm in the past 60 minutes and humidity above 55.8% increase cyclists' self-estimated level of traffic accident risk	Singapore

Hanson and Hanson, 1977	household travel survey among 300 households	correlation analysis, regression analysis	daily volume of discretionary trips (i.e. social, shopping, personal business, recreational purposes) was not influenced by temperature, precipitation and cloud cover; however temperature had significant linear impact (R2=0,62) on percentage of daily discretionary stops made by bicycle; percentage of daily trips to work by bicycle increased when temperature increased and decreased with greater cloud cover	Sweden
Bergström and Magnusson, 2003	questionnaire survey among thousand employees at 4 major companies in 2 cities	descriptive statistics	*survey in 1998 and 2000; estimating the importance of certain factors (i.e. temperature, accident risk, road condition, travel time, cost, precipitation, errands, darkness, car park, environment, and exercise) for mode choice when travelling to work by bicycle; score 1 denoted "no importance" and 7 denoted "great importance"* impact of weather conditions differs between cyclists with different experience (winter cyclists, summer-only cyclists and never cyclists); in a questionnaire survey in 1998, temperature had the biggest impact on summer-only cyclists (score 5.47) and it was the most important factor; the score for temperature was 3.22 (8th place out of 11) for winter cyclists. and 3.29 (5th place out of 11) for never cyclists; in 1998 precipitation was ranked in 7th place by winter cyclists (score 3.34), in 2nd place by summer-only cyclists (score 5.27), and in 4th place by never cyclists (score 3.53); in 2000 scores for temperature and precipitation were similar to those obtained in 1998; temperature and precipitation were scored 2.54 (9th place out of 10) and 3.1 (7th place), 5.16 (3rd place) and 5.71 (1st place), 3.78 (4th place) and 4.26 (3rd place) by winter cyclist, summer-only cyclist and never cyclists, respectively; total score for temperature and precipitation (for all cyclists) was 3.91 (4th place out of 11) and 4.0 (2nd place), 3.59 (7th place out of 10) and 4.16 (5th place) in the surveys conducted in 1998 and 2000, respectively; darkness was the least important in mode choice decision; total score for darkness was 2.47 and 2.37 in the survey in 1998 and 2000, respectively; darkness had the strongest impact on summer-only cyclists and the weakest on winter cyclists	
Noland and Ishaque, 2006	questionnaire survey among 46 bikeshare system users	descriptive statistics	10% and 50% of daily bicycle trips were taken on days with maximum temperature up to 15°C and above 20°C respectively; 70% of bikeshare trips were made in days with no rain.; number of hours of sunshine had little effect on bikeshare system users	UK
Parkin, Wardman and Page, 2008	national travel survey data	logistic regression model	higher mean air temperature increased share of trips done by bicycle to work; rainfall had a relatively high negative impact on share of bicycle trips to work	
Dill and Carr, 2003	census data for 35 cities	descriptive statistics, regression analysis	number of days of rain per year did not have clear impact on mode choice	
Buehler and Pucher, 2012	census data (share of workers regularly commuting by bicycle)	Pearson's correlation, bivariate quartile analysis, regressions analysis	*asked question: ''How did you usually get to work last week?''* cyclist volume was lower in cities with more days with temperatures above 32.2ºC per year; in cities with more annual precipitation the share of bicycle trips was lower but the relationship between annual inches of precipitation and share of bicycle trips was not statistically significant	
Flynn *et al.*, 2012	questionnaire survey among 163 working adults (reports of travel)	generalized linear model	respondents were 2 time more likely to commute by bicycle when there was no morning precipitation; likelihood of bicycle commuting increased by 3% and 91% when temperature increases by 1°C and in the absence of rain respectively, and decreased by 10% with 1 inch of snow on the ground; 1.6kph increase in wind speed decreased the likelihood of travelling to work by bicycle by 5%	

Sabir, 2011	questionnaire survey on travel behavior during a certain day (154 261 leisure trips in total)	negative binomial model, Tobit model, descriptive statistics for	compared with temperature 0-10ºC, the number of individual daily bicycle trips decreased by 7.76% when the temperature did not exceed 0ºC and increased by 9.19%, 18.11%, 21.95% in temperature 10-20ºC, 20-25ºC and above 25ºC, respectively; average daily distance travelled per person decreased by 13.04% and increased by 22.17%, 49.57%, 57.83%, in temperature below 0ºC, in range 10-20ºC, 20-25ºC and above 25ºC, respectively compared to temperature 0-10ºC; overall bicycle share decreased by 2.966% when the temperature did not exceed 0ºC and increased by 3.85%, 9.55%, 13.16% in temperature 10-20ºC, 20-25ºC and above 25ºC, respectively, compared with temperature 0-10ºC.; compared with no precipitation, the number of individual daily bicycle trips and average daily distance travelled by bike per person decreased by 5.2% and 1.74% (with precipitation up to 0.1 mm) and by 7.89% and 11.74% (with precipitation greater than 0.1 mm), respectively; the overall percentage share of bike trips decreased by 2.84% with precipitation up to 0.1 mm; greater amount of precipitation decreased bicycle share, but the change was not statistically significant; no statistically significant influence of snow on the number of individual daily trips and average daily distance travelled per person was found, but snow resulted in a statistically significant increase in percentage share of bicycle trips by 2.36%; strong wind (38.6-49.7kph) decreased average daily distance travelled by bike per person and percentage share of bicycle trips by 13% and 5.9%, respectively, compared with light wind; no statistically significant influence of strong wind on a number of individual daily trips was found	Netherlands

Table 3. Results of empirical research on impact of weather on bicycle use

Source	**Method of bicycle use data gathering**	**Method of data analysis**	**Results**	**Country of origin**
Phung and Rose, 2007	automatic counters at 13 locations	multivariate log-linear model, descriptive statistics	light rain (daily rainfall < 10mm) deterred 8-19% of all cyclists from bike riding, heavy rain (daily rainfall >10mm) deterred 13-25%; additional hour of sunshine in a day increased daily bicycle volume by 1.5-5%; strong wind (40-62kph) reduced commuter cyclist volume by 11-23%; light wind (20-39kph) had not impact; ideal temperature for bike riding was found to be 28ºC.	Australia
Ahmed, Rose and Jacob, 2010	automatic counters at 4 locations	descriptive statistics, multivariate log-linear model	light rain (<10mm) and heavy rain (>10mm) decreased bicycle volume by 13% and 40% respectively; strong wind (40-62kph) decreased cyclists volume by 15-20%; ideal temperature for bike riding was found to be 25-28ºC; in that temperature bicycle volume increased by 60% compared to 0ºC; additional hour of sunshine decreased bicycle volume by 1-4%	
Corcoran *et al.*, 2014	bikeshare system trip data (285 714 trips in total)	multivariate regression model, spatial flow analysis, flow-comap	in temperatures higher than 21ºC number of bikeshare trips taken increased by 12% compared to lower temperatures (up to 21ºC), however temperature was not found to have a statistically significant impact on number of bike trips taken; in rainy days the number of bikeshare trips decreases by 31% compared with days with no rain; strong wind (>5kph) reduced the number of bicycle trips by 17%, compared to light wind (<5kph)	
Miranda-Moreno and Nosal, 2011	automatic counters at 5 locations	log-linear models, count data regression models	when temperature doubled, bicycle volume increased by 43-50%, but when humidity doubled it decreased by about 58%; temperature increase by 10% from the mean resulted in increase of bicycle volume by 4-5%; when rain was present in the 3 previous hours, hourly bicycle volume decreased by 25-36%; when it was raining in the morning, but not in the afternoon, bicycle volume decreased by 13-15%; hourly bicycle volume decreased by 19% when there was rain with fog, drizzle, and/or freezing rain during that hour	Canada

Gallop, Tse and Zhao, 2012	automatic counters at 4 locations	ARIMA	increase of 1°C from the mean temperature increased bicycle volume by 1.65%; average hourly bicycle volume decreased by 24% (50 trips per hour) as the effect of rain and its lags; cyclist volume decreased by 0.62% at each of the four defined categories, i.e.: cloudy, mostly cloudy, mainly clear, clear; 1% change in relative humidity resulted in a decrease in bicycle volume by only 0.08%	Canada
Wessel, 2020	automatic counters at 188 locations	log-linear and negative binomial regression models	forecasted daily high air temperature had a positive effect and forecasted clouds, rain, snow, thunderstorms, or weather warnings had a negative effect on bicycle volume; actual weather and forecasted weather are both important determinants of bicycle use; bicycle volume was lower by 3,6% and higher by 11,5% for hours with no rain but for which rain was forcasted and for hours with rain but for which rain was not forcasted, respectively, compared to hours with correctly forecasted rain; even if midday and afternoon hours were predicted to be rain-free, rain forecasted for the morning hours significantly reduced bicycle volume ; impact of weather (actual and forecasted) for recreational counting stations was stronger than for utilitarian ones.	Germany
Thomas, Jaarsma and Tutert, 2009	automatic counters at 16 locations	correlation analysis, bi-level model (linear and non-linear relationships)	recreational trips were much more sensitive to weather conditions than utilitarian trips; temperature, sunshine, precipitation, wind speed had significant impact on bicycle volume, but humidity and visibility did not	Netherlands
Thomas, Jaarsma and Tutert, 2013				
Tin *et al.*, 2012	automatic counters at 1 location	Spearman rank correlation analysis, multivariate linear regression model	daily and hourly bicycle volume increased by 2.6% and 3.2% respectively for each 1°C increase in temperature; daily bicycle volume decreased by 1.5% and hourly bicycle volume decreased by 10.6% for a 1mm increase in rainfall during that day or hour respectively; hourly bicycle volume was 26.2% higher in hours with sunshine compared with hours with no sunshine; additional hour of sunshine in a day increased daily bicycle volume by 2.5%; a 1 km/h increase in wind speed resulted in a decrease in daily and hourly bicycle volume by 0.9% and 1.4%, respectively	New Zealand
Mathisen, Annema and Kroesen, 2015	automatic counters at 1 location	econometric model	bicycle rate was more influenced by wind speed, than by temperature; the lowest effect had precipitation; reduction in temperature and increase in wind and rain by 1 standard deviation reduced the bicycle rate by 1.20, 0.61 and 0.31 respectively; increase in temperature and reduction in wind and rain by 1 standard deviation increased the bicycle rate by 1.68, 0.71 and 0.18 respectively	Norway
Öberg, 1998	continuous record *(no detailed information)*	descriptive statistics	bicycle volume decreased by 40% and 60% at slight precipitation and heavier precipitation respectively (no detailed information provided what slight and heavier precipitations meant); bicycle volume was reduced by 50%, under ice and snow conditions compared to clear road surface	Sweden
Lewin, 2011	automatic counters in 2 locations	linear regression model, descriptive statistics	bicycle volume decreased on days with rain or snow; this relationship was not linear	UK
Ashqar, Elhenawy and Rakha, 2019	bikeshare system data (number of bikes available at each station)	Poisson and negative binomial regression models, Random Forest, Bayesian Information Criterion	temperature and humidity had significant impact on number of available bikes at bikeshare system stations, but precipitation did not	

Gebhart and Noland, 2014	bikeshare system trip data (1 361 074 trips)	negative binomial model, ordinary least squares regression model	registered users and casual users made respectively 48.5% and 68.3% fewer trips per hour in the rain compared with no rain conditions; trip duration decreased by 10.1% and 22.4% in the rain and by 9.4% and 12.1% in the snow for registered users and casual users respectively; fog and thunderstorms slightly increased trip duration for registered users (by 0.2% and 4.4% respectively) but decreased trip durations for casual users (by 36.1% and 29.3%, respectively); darkness resulted in a reduction in bicycle trip frequency of about 1-1.25; when it was dark bicycle trips were 3.1 minutes shorter; 1% change in the mean value of humidity (equal 63.86%) was related to a reduction in the frequency of bicycle trips by 0.91-0.94%	UK
Ermagun, Lindsey and Hadden Loh, 2018	32 traffic monitoring stations on multiuse trails in 13 cities in USA	negative binomial regression models	cyclists were more sensitive to daily average temperature, precipitation and average wind speed than pedestrians; 1% increase in the average daily temperature increased the bicycle volume by 3.2%; 1% increase in the average wind speed decreased bicycle demand two times more than pedestrian demand	USA
An *et al.*, 2019	bikeshare system trip data from 1 year	flow-comap, regression models	weather had greater impact on bicycle use than topography, infrastructure, land use mix, calendar events, and peaks; air temperature had positive impact on bicycle use, while rain,snow and wind speed were found to have negative impact on number of bicycle trips; impact of weather arameters on bicycle use differed in weekends and weekdays	

2.2.1. Weather parameters affecting bicycle use

Weather parameters found to have a significant impact on cyclists' volume are the following: air temperature, precipitation, sunshine, cloud cover, humidity, and wind strength. Impact of weather conditions on bicycle use was previously described in reference to daily number of trips made by public bicycle (Noland and Ishaque, 2006), (Gebhart and Noland, 2014), (An *et al.*, 2019) daily and/or hourly bicycle volume (Miranda-Moreno and Nosal, 2011), (Gallop, Tse and Zhao, 2012), (Tin *et al.*, 2012), likelihood of bicycle commuting (Flynn *et al.*, 2012), time spend on cycling (Winters *et al.*, 2006), (Gebhart and Noland, 2014), average daily bicycle trip rate (Saneinejad, Roorda and Kennedy, 2012), number of cyclists per 1000 inhabitants per day (Mathisen, Annema and Kroesen, 2015).

Temperature was found to have a non-linear effect on bicycle volume (Miranda-Moreno and Nosal, 2011), (Richardson, 2000), (Phung and Rose, 2007), (Corcoran *et al.*, 2014), (Lewin, 2011), (Gebhart and Noland, 2014). An increase in temperature leads to an increase in bicycle volume, but when the temperature exceeds the threshold value, cyclist volume decreases. In (Miranda-Moreno and Nosal, 2011) temperature had a negative effect on bicycle volume when it was higher than 28ºC. Authors of (Saneinejad, Roorda and Kennedy, 2012) noticed that cyclists became sensitive to temperature when it was below 15°C. Ideal temperature for bicycle riding was found to be 25ºC (Richardson, 2000), 28ºC (Phung and Rose, 2007), and 32.2ºC (Lewin, 2011), (Gebhart and Noland, 2014). Research (Gebhart and Noland, 2014) showed that most bike trips were made when temperature was in the range 26.7–31.7ºC. Similars results were presented in (Meng *et al.*, 2016) were cyclists preferred a temperature in the range 29.5–31.5°C. In (Buehler and Pucher, 2012) cyclist volume was lower in cities with more days with temperatures above 32.2ºC per year. Similarly to air temperature, in (Richardson, 2000) and (Phung and Rose, 2007) non-linear effect of the rainfall on bicycle volume was noticed. Previous studies show that hourly bicycle volume depends not only on rainfall in that hour but also on rainfall in the previous 3 hours or in the morning (Miranda-Moreno and Nosal, 2011), (Gallop, Tse and Zhao, 2012).

Number of weather parameters included in the analysis and their variability affects which weather parameters have statistically significant impact on bicycle use. For example in (Nankervis, 1999) only 3 factors were included in the analysis, i.e. wind, rain and temperature. Hours of sunshine, cloud cover and humidity, which were statistically significant determinants of bicycle volume in other research, were not considered, and of course their impact on cycling was not reported. Authors of (Tin *et al.*, 2012) did not find a non-linear effect of temperature on bicycle use. It could be the result of lack of extreme temperatures in analysis period. Air temperature, found to have major impact on bicycle volume in many research, was not statistically significant in (Corcoran *et al.*, 2014). The reason might be small variability of temperature or the way it was analyzed (i.e. two categories of temperature were taken into consideration: low (up to 21°C) and high (above 21°C)). Variability of weather parameters is also an effect of adopted analysis period. For example in (Hanson and Hanson, 1977) 39 days of the analysis was too short to find strong relationships between cycling and weather conditions.

In (Sabir, 2011), (Nankervis, 1999), (Bergström and Magnusson, 2003), (Lewin, 2011) variability of bicycle volume in terms of season change (spring, summer, autumn, winter) was analyzed. It is worth to mention that season is strictly correlated with air temperature, precipitation, and humidity. Using seasons rather than weather parameters is an indirect method to evaluate their impact on cycling. However, correlation coefficients between seasonal and weather parameters should be analyzed. Using the seasonal coefficient of variation of bicycle volume enables a general estimation of change in bicycle use due to changing weather conditions (seasons). Nevertheless, it is not useful when changes in bicycle volume are analyzed in a shorter period of time (week, day, hour).

2.2.2. Methods of bicycle use data gathering

In the previous research two main methods of bicycle use data gathering were used, i.e. survey and empirical data (from automatic counters or bikeshare systems).

Survey research were done in two different ways:

- survey of the preferences (Ahmed, Rose and Jacob, 2013), (Winters *et al.*, 2006), (Winters *et al.*, 2011), (Bergström and Magnusson, 2003) – show general trends and tendencies to make a trip by bicycle in various weather conditions, allow to assess and rank weather factors in terms of its impact on cycling in comparison to other factors affecting mode choice (infrastructure, time of travel, etc.), often made including different travel motivations, age groups, gender and cycling experience. In these studies, the assessment is often carried out in a qualitative way, e.g. in (Winters *et al.*, 2011) and (Bergström and Magnusson, 2003) authors used scores from -1 up to 1 (every 0,5) and from 1 to 7 (every 1) respectively. The results of these studies do not allow to estimate the change in bicycle volume for given values of weather parameters, but give in-depth insight into the decision-making process whether to cycle. Therefore results of those survey are a valuable complement to empirical research and can be used by road administration (what can we do to encourage people to cycling?, on what group of potential cyclists should we focus?);
- research based on trips that were actually made (Sabir, 2011), (Richardson, 2000), (Saneinejad, Roorda and Kennedy, 2012) – analyzed together with weather parameters data from weather stations. Relationship developed in these type of studies allow to evaluate change in bicycle volume for given values of weather parameters.

Not only weather conditions, but also age, gender, physical fitness, travel motivation, accessibility to bicycle, cycling experience, trip distance, type and standard of bicycle infrastructure, perceived safety level, presence of parking, public transport fares, time of trip, etc. have an impact on mode choice. Therefore, when planning survey research a great effort should be put into choosing the right group of respondents (Saneinejad, Roorda and Kennedy, 2012), (Flynn *et al.*, 2012). When assessing the potential increase in bicycle volume, it should be remembered that some people will not choose bicycle as a mode of transport, no matter what actions will be taken (improvement of bicycle infrastructure, etc.).

Automatic counters are the main source of bicycle volume data. Cyclists can use dedicated infrastructure, roadway or pedestrian paths. Using bicycle volume data from automatic counters is a adequate approach for separated bicycle paths, but may generate error when bicycle infrastructure located next to pedestrian path or a roadway is analyzed. Another limitation in automatic counters usage is an error arising when two or more cyclists ride together or ride with high speed. To eliminate those problems bicycle GPS data could be used in the analysis (Pogodzinska, Kiec and D'Agostino, 2020).

2.2.3. Methods of weather data gathering

Based on (Gallop, Tse and Zhao, 2012), 58% of cyclists considered the weather when deciding whether to cycling, and 77% of them based their decision on current rather than forecasted or recent weather. Among respondents who based their decision on forecasted weather, 41% checked it just before they leave, 24% up to 2 hours before and 29% on the evening before. For comparison, (Ahmed, Rose and Jacob, 2013) found that about half of the respondents planed which days they will bike ride in advance and 49% of commuters considered current weather conditions as well as forecasted weather when planning their trips. It should be noticed that forecasted weather, which is also the basis of decision making process, can be different than data from weather station, which were mainly used in the previous research.

In previous research, models describing impact of weather on bicycle use were developed using both quantitative and qualitative weather measures. In (Gallop, Tse and Zhao, 2012) if fog, rain, snow or drizzle were present, dummy variable was 1 (if not, it was 0). Nankervis used categories of rain, wind and temperature (Nankervis, 1999), Saneinejad et al. distinguished five sky conditions and nine temperature categories (Saneinejad, Roorda and Kennedy, 2012), Brandenburg et al. used two precipitation categories (with and without precipitation) and thermal index (Physiologically Equivalent Temperature, PET) based on temperature categories. Using categories rather than direct measures of weather variable may impede finding relationship between that parameter and bicycle volume, like it could be in (Corcoran *et al.*, 2014), where air temperature was not statistically significant determinant of bicycle volume. It can also not allow to observed non-linear impact of weather parameter on bicycle use.

Different measures of weather parameters should be taken into consideration. For example in majority of previous research rain was represented by its amount in mm. However, using intensity of the rain (in mm per hour or day) rather than its amount can help find new and different relationships (Sabir, 2011). Interesting approach was used in (Phung and Rose, 2007), (Ahmed, Rose and Jacob, 2010) where apparent temperature (dependent on humidity, wind strength and air temperature) rather than air temperature alone was analyzed.

2.2.4. Methods of data analysis

Research based on observed data were conducted with reference to hourly or daily bicycle counts. In general, compared to models build for daily volumes, relationships for hourly volumes were worse fitted to empirical data (analysis with reference to hourly data: R^2= 0,38-0,59 (Miranda-Moreno and Nosal, 2011); R^2 = 0,30-0,60 (Ahmed, Rose and Jacob, 2010), R^2 <0,19 (Gebhart and Noland, 2014); analysis with reference to daily data: R^2 = 0,79 (Thomas, Jaarsma and Tutert, 2013), R^2= 0,52-0,71 (Brandenburg, Matzarakis and Arnberger, 2007), R^2=0,68 (Mathisen, Annema and Kroesen, 2015), R^2=0,78-0,85 (Lewin, 2011)). In (Tin *et al.*, 2012) weather factors explained 23% and 56% of the variability of hourly and daily bicycle volume respectively. However, when using daily data impact of change of weather conditions during the day on bicycle use cannot be analyzed. According to (Thomas, Jaarsma and Tutert, 2009), total amount of precipitation for wet night followed by a sunny day and dry night followed by a wet day may be the same, however impact on bicycle use can be different. Therefore, like Richardson suggested (Richardson, 2000), because most bicycle trips are made in daylight hours, it may be better to use daylight-hour rainfall in the analysis. The same could be adopted for other weather parameters.

In previous research, regression models were the main method of data analysis. In (Gallop, Tse and Zhao, 2012) two methods were implemented i.e. linear regression and ARIMA model, characterized by R^2=0,35 and R^2=0,95, respectively. It suggests that using more sophisticated methods of data analysis can help to develop model better fitted to empirical data.

2.2.5. Factors differentiate the impact of weather on bicycle volume

Cyclists are more exposed to weather conditions than e.g. car drivers, and therefore their decision of whether to cycle is strongly related to personal comfort. As mentioned in (Sabir, 2011), (Thomas, Jaarsma and Tutert, 2013), (Brandenburg, Matzarakis and Arnberger, 2007), (Saneinejad, Roorda and Kennedy, 2012), (Hanson and Hanson, 1977), (Bergström and Magnusson, 2003), (Thomas, Jaarsma and Tutert, 2009), (Gebhart and Noland, 2014) personal comfort, and as a result the impact of weather conditions on bicycle volume, differ between cyclists' groups (different level of experience, age, gender) and trip motivation. In general, recreational cyclists (who are less experienced and ride from time to time) are more sensitive to bad weather conditions than commuting cyclists (who are more experienced and ride frequently).

It may be confusing that some of the research results described in the paper show such a different impact of weather on bicycle volume, even though they were made in the same country or even city. For example, in (Richardson, 2000) author calculated that daily rainfall of around 8 mm resulted in a 50% decrease in bicycle volume, compared to days with no rain. On the other hand, in (Phung and Rose, 2007) it was found that cyclists' volume decreased by 8-19% if daily rainfall was 0.2-10mm. Both research was conducted in the city of Melbourne (Australia). Nevertheless, research (Richardson, 2000) was based on a questionnaire survey made in 1994 and research (Phung and Rose, 2007) was made over 10 years later, based on a data from automatic counters. Moreover, in (Phung and Rose, 2007) wind with strength of 40-62kph resulted in a reduction in commuter cyclist volume by 11-23%. On the other hand, (Corcoran *et al.*, 2014) showed that wind with strength already above 5 km/h reduced the number of bicycle trips by 17%. Research by (Corcoran *et al.*, 2014) was also conducted in Australia, however in the city of Brisbane and in reference to bikeshare system users. Different methodology used and time of data gathering may be the explanation for the observed differences in research results. It shows that implementation of models describing the relationship between weather conditions and bicycle volume developed for different locations and time, related to specific group of cyclists should be done very carefully.

3. Evaluation of impact of weather on predicted number of crashes with cyclists

Review of previous research results indicates that bicycle volume is significantly influenced by weather conditions. The impact of weather on a predicted number of accidents involving cyclists was estimated using own road safety models (not published) and previous research results.

3.1. Evaluation based on own safety models

Based on inventory of over 50km of selected street sections in City of Cracow, a database of factors that may affect cyclists' safety for 171 homogenous road segments was collected. For each homogenous segment, the database included: road parameters (length of the segment, street function, the number of lanes and roadways, speed limit), type and standard of bicycle infrastructure (width, type of the pavement, offset from the roadway edge, bicycle traffic separated or mixed with other road users), access to road (the number of public and residential access points), crossings with pedestrian and vehicles (the number of crossings, traffic management at crossings), public transport (the number of bus stops), parking (presence and angle of parking, the number of parking spots), as well as number of crashes with cyclists (based on crash data from 2015-2017) and Annual Average Daily Bicycle Traffic (AADBT) estimated based on bikeshare system GPS data (Pogodzinska, Kiec and D'Agostino, 2020). Three Generalized Linear Models (GLMs) with negative binomial distribution of dependent variable i.e. number of crashes with cyclists, were developed. The models forms are shown in equations 1-3 and the results of calibration are shown in Table 4.

$$Cr = e^{\alpha_1} * AADBT^{\beta_1} * L^{\gamma_1} * e^{\delta_1} \tag{1}$$

$$Cr = e^{\alpha_2} * AADBT^{\beta_2} * L^{\gamma_2} * e^{\delta_2 * off} \tag{2}$$

$$Cr = AADBT^{\beta_3} * L * e^{\delta_3} \tag{3}$$

where*:*

Cr - predicted number of crashes with cyclists [Cr/3years],

AADBT - Annual Average Daily Bicycle Traffic [Bicycles/24h],

L - length of segment [km],

off - offset of bicycle traffic from the roadway edge [m],

α, β, γ - regression terms of the continuous variables [-] (Table 4),

δ - regression term of the categorical variables [-] (Table 4).

AADBT and length of road segment are independent variables in all models. Additionally, to evaluate impact of various infrastructure characteristics on cyclists safety, each model includes different independent variable i.e. cross section– Model 1, offset of bicycle traffic from the roadway edge – Model 2, type of bicycle infrastructure – Model 3.

Figure 2 shows a relative change of predicted number of crashes with cyclists due to relative change of AADBT. It should be mentioned that AADBT is also indirectly included in independent variables i.e. cross-section, type of infrastructure used by cyclists and its offset from a roadway edge. Therefore, models present differences in impact of AADBT change on predicted number of crashes with cyclists. However, those differences are not significant. Model 3 is the least and Model 1 is the most sensitive on AADBT change. Relative change of AADBT in range 0,5-2,0 results in relative change of predicted number of crashes with cyclists in range 0,72-1,38. For example, if AADBT increase by 10%, predicted number of crashes with cyclists increase by about 5%.

Presented models can be used to evaluate impact of weather in a longer period (e.g. impact of rainy summer or warmer winter, which result in change in AADBT) or when climate change is considered.

Table 4. Regression coefficient, standard error, and p-value of the crash prediction models

Parameter		Symbol	Estimate	Standard error	95% confidence interval		Chi-Square	p-value
Model 1								
Intercept		α_1	-5.159	1.417	-7.937	-2.382	13.253	<0.001
AADBT		β_1	0.463	0.141	0.186	0.740	10.756	0.001
Lenght		γ_1	0.559	0.187	0.193	0.925	8.973	0.003
Cross section	one-lane road	δ_1	2.904	1.123	0.702	5.106	6.684	0.010
	two-lane road		3.475	1.134	1.251	5.698	9.380	0.002
	four-lane road with median		2.826	1.071	0.727	4.924	6.967	0.008
	not relevant (*)		0.000					
Dispersion			0.794	0.315	0.364	1.729		
Model 2								
Parameter		Symbol	Estimate	Standard error	95% confidence interval		Chi-Square	p-value
Intercept		α_2	-1.899	0.779	-3.425	-0.373	5.950	0.015
AADBT		β_2	0.412	0.139	0.140	0.684	8.792	0.003
Lenght		γ_2	0.499	0.189	0.130	0.869	7.007	0.008
Offset		δ_2	-0.093	0.042	-0.176	-0.010	4.808	0.028
Dispersion			1.006	0.374	0.486	2.085		
Model 3								
Parameter		Symbol	Estimate	Standard error	95% confidence interval		Chi-Square	p-value
AADBT		β_3	0.382	0.162	0.065	0.700	5.581	0.018
Infrastructure used by cyclists	sidewalk	δ_3	-3.107	0.823	-4.719	-1.494	14.257	< 0.001
	pedestrian/ bicycle path		-3.132	0.990	-5.072	-1.193	10.018	0.002
	bicycle lane		-2.750	1.176	-5.055	-0.445	5.468	0.019
	bicycle path		-3.353	1.096	-5.501	-1.205	9.363	0.002
	roadway		-2.706	0.860	-4.393	-1.020	9.894	0.002
Dispersion			1.111	0.388	0.561	2.202		

(*) when bicycle traffic is moved away from a roadway for more than 10m

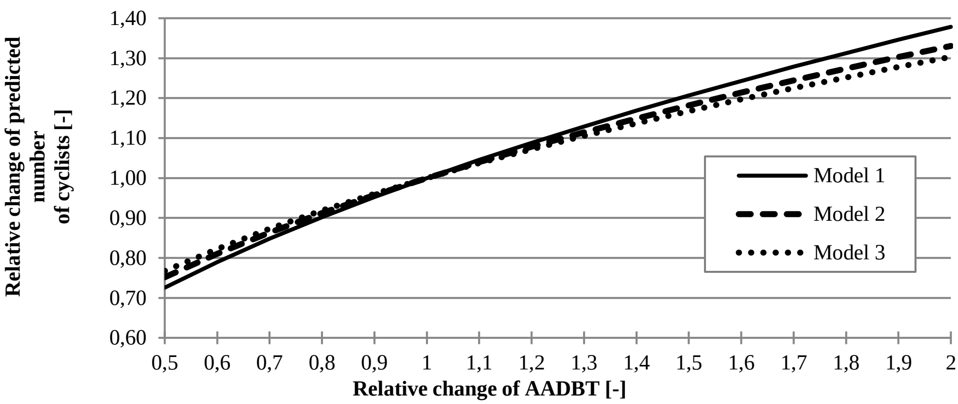

Fig. 2. Relative change of predicted number of crashes with cyclists due to relative change of AADBT

3.2. Evaluation based on previous research results

To evaluate impact of weather on bicycle use in a shorter period bicycle crash models described in (Kröyer, 2016), (Schepers *et al.*, 2011), (Amoh-Gyimah, Saberi and Sarvi, 2016) were used. Table 5 presents example changes in predicted number of crashes with cyclists due to changes in weather conditions. For example, based on models from (Tin *et al.*, 2012) and (Kröyer, 2016), if temperature increases by 5°C, daily bicycle volume increases by 13% (2,6%*5), and therefore a number of bicycle single crashes increases by 9%. For comparison, according to models developed in (Flynn *et al.*, 2012) and (Amoh-Gyimah, Saberi and Sarvi, 2016), if temperature increase by 5°C likelihood of commuting to work by bicycle increase by 15% (3%*5), and therefore number of crashes with cyclists increase by 6%.

Presented calculations show that small change in weather conditions, especially in air temperature and precipitation, results in significant change in predicted number of crashes with cyclists.

Table 5. Relative change in predicted number of crashes with cyclists due to change in weather conditions

			Source of crash model				
			Kröyer, 2016		(Schepers *et al.*, 2011) bicycle - motor vehicle crashes		(Amoh-Gyimah, Saberi and Sarvi, 2016) negative-binomial model based on commuters cycling to work
Source of bicycle volume change	**Impact on bicycle volume**	**Weather change**	bicycle single crashes	bicycle - motor vehicle crashes	cyclist on priority road	car on priority road	
		Temperature					
Flynn *et al.*, 2012	increase by 3% for each 1°C increase	5°C increase					1,06
Tin *et al.*, 2012	increase by 2.6% for each 1°C increase		1,09	1,05	1,06	1,07	
Ahmed, Rose and Jacob, 2010	in 25-28oC bicycle volume increase by 60% compared to 0°C;	25-28°C	1,37	1,22	1,25	1,30	
Corcoran *et al.*, 2014	number of bikeshare trips taken increase by 12% in temp. higher than 21°C, compared to lower temp.	higher than 21°C	1,08	1,05	1,06	1,07	
		Rain, snow					
Richardson, 2000	decrease by 50% for daily rainfall 8mm	8mm	0,63	0,74	0,72	0,68	
Flynn *et al.*, 2012	increase by 91% when there is no rain	no rain					1,34
Flynn *et al.*, 2012	decrease by 10% during snow	snow					0,95
Tin *et al.*, 2012	decrease by 1,5% for each 1mm increase	5mm increase	0,95	0,97	0,96	0,96	
		Sunshine					
Phung and Rose, 2007	increase by 1,5-5% for additional hour of sunshine	2h more	1,02 - 1,07	1,01 - 1,04	1,01 - 1,05	1,02 - 1,05	
Tin *et al.*, 2012	increase by 2,5% for additional hour of sunshine		1,03	1,02	1,02	1,03	
		Wind speed					
Phung and Rose, 2007	strong wind (40-62kph) reduce commuter cyclist volume by 11-23%	40-62kph					0,89-0,95
Tin *et al.*, 2012	decrease by 0,9% for each 1kph increase	10kph	0,94	0,96	0,96	0,95	

4. Conclusions and recommendations for future research

Weather conditions i.e. air temperature, precipitation, sunshine, cloud cover, humidity, and wind strength, have a significant influence on bicycle use. The impact of the weather on bicycle volume differs between different cyclists' groups (different levels of experience, age, gender), trip motivations (recreational, commuting, etc.) and locations (countries, cities, climate zones). The paper shows complexity of impact of weather conditions on cycling and sensitivity of relationship between weather conditions and bicycle volume (i.e. risk exposure) and, as a consequence, bicycle safety. It suggests that weather conditions should be considered in every analysis where bicycle volume data is needed. Additionally, while the weather has such a strong impact on bicycle volume, including the variability of cyclists' risk exposure (i.e. bicycle volume) due to changing weather conditions would give a more insightful estimation of the impact of weather parameters on the number of accidents with cyclists and their severity.

Although there have been many studies estimating the impact of weather on bicycle volume, there are some gaps which could be filled in future research. Bikeshare systems are implemented in an increasing number of cities. Public bicycles, which are equipped with GPS devices, allow to collect big data of bike trips. Because of the difficulties in bicycle traffic data gathering (small number of automatic counters, multitude of factors affecting bicycle use, etc.), the use of GPS technology and finding relationships between traffic flow parameters of bikeshare systems (or Strava and similar apps) users and all population of cyclists, would be useful in cyclists mobility analyses, especially in the specific period (like current COVID-19 pandemic), where traffic distribution models may not be adequate. However, the assumption that bikeshare system users are a random sample of the entire population of cyclists, and the trip parameters of this group of cyclists are related to the characteristics of the entire bicycle flow has to be verified. According to eg. (Sabir, 2011), (Thomas, Jaarsma and Tutert, 2013), (Brandenburg, Matzarakis and Arnberger, 2007), (Saneinejad, Roorda and Kennedy, 2012), (Bergström and Magnusson, 2003), (Gebhart and Noland, 2014) the effect of the weather differs between different cyclist groups. However, no research has been conducted to evaluate differences in the influence of weather conditions on bikeshare system users and other cyclists. Bikeshare system users may be less sensitive to weather change during the day. They may rent a bike for morning commute and change mode of transportation for the return trip if it starts to rain. On the other hand, private bike ensures a "door to door" trip. Bikeshare system users may have to rent and leave a bicycle at a station, which can be located far away from their destination. During rain or colder temperature, this additional trip which has to be made e.g. on foot, may discourage cyclists from using the system. Public bicycles are often used by tourists. In the summer, when the number of tourists in the city grows, the increase in public bicycles volume can be more dynamic than the increase in the volume of other cyclists. However, the number of bikes in the system is limited. As a result, an increase in the volume of public bicycles is also limited. Moreover, in the colder months the number of bicycles in the system may be reduced. For example, in Cracow (Poland) from 1st December 2018 to 28th February 2019, only 1/3 of public bicycles were available. As a consequence, even though there was a warmer and sunny week in February, the increase in public bicycle volume was limited. All of the factors mentioned above indicate that weather conditions may have a different impact on bikeshare system users and other cyclists. However, analysis in this area has to be made.

It is worth to mention that users of small electric vehicles (e.g. scooters and skateboards) are exposed to weather conditions in the same way as cyclists are. They often use bicycle infrastructure to ride and can achieve similar speeds to cyclists. The growing popularity of those types of vehicles in cities around the world expose the necessity of undertaking research also with reference to them (including research on impact of weather on their demand). However research in this area is relatively new.

There was some research on the impact of climate changes on bicycle volume in a long time perspective (Ahmed, Rose and Jacob, 2010), (Mathisen, Annema and Kroesen, 2015). However, change in weather should be also considered in short term analyses. In (Miranda-Moreno and Nosal, 2011) authors reported that bicycle ridership rate increased by 50% during 2 years period. Because of significant impact of weather on bicycle use, cyclists' volume data should be analyzed together with weather data. Assuming that there were no improvements in bicycle infrastructure, the change in bicycle volume in subsequent years is strictly related to weather change. As a consequence, a decrease in bicycle volume e.g. in a colder summer may be the effect of lower temperatures, not only the effect of a change in the popularity of cycling or transportation mode share.

The paper considers only bicycle volume, however weather conditions should be also included when other bicycle trip characteristics are analyzed (e.g. speed (Strauss and Miranda-Moreno, 2017)).

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