Long Term Effects of the Pandemic on Urban Mobility: the case of free-floating bike sharing in Padova

Abstract

The spread of Covid-19 virus all around the globe has drastically changed our lifestyles and our habits. Among all aspects affected by the pandemic, mobility has certainly undergone huge changes. Understanding these changes is crucial for the improvement of future urban planning. Since the world is moving in the direction of a more sustainable mobility, our analysis has focused on bike sharing systems and we have utilized the city of Padova (Italy) as case study. In particular we have analysed the data relative to three periods that are representative of Pre-Pandemic, Pandemic and Post-Pandemic worlds. We have highlighted the effects of the pandemic on bike sharing users' behaviors not only during the emergency period, but mostly with a long-term perspective. We have observed an increase of the total amount of rides, as well as an expansion of the service towards more peripheral areas, and a greater predisposition to use the bike in the free time or when the weather conditions are not ideal.

Keywords: Bike Sharing; Free Floating; Covid-19; Post-Pandemic World

1. Introduction

On December 31 2019 the Chinese health authorities notified an outbreak of pneumonia cases of unknown etiology in the city of Wuhan. On January 9 2020 the China Center for Disease Control and Prevention identified a new coronavirus, the 2019-nCoV. Two months later, on March 11, the World Health Organisation officially declared that COVID-19 epidemic had became a pandemic. From that moment on the world drastically changed. According to ISTAT, the Italian National Institute of Statistic, during the emergency in Italy 72951 companies temporarily closed. The percentage of workers from home grew from 3,6% (2019) to 12,2% (2020), as reported from EUROSTAT. For several months it was not possible to travel to other countries or other regions. Inside the cities the life completely changed due to the necessity of social distancing. Utilize public transportation was considered dangerous since the virus could easily spread through crowds, specially in enclosed spaces such as buses or trains (Zheng et al., 2020). For this reason the demand for public transport in 2020 in Italy fell of 47,9% with respect to 2019. A similar scenario occurred in most countries, where the pandemic led to a significant decrease in mobility, both in terms of number of trips per day and distance per trip (Politis et al., 2021).

Even if today the emergency is almost over, some of the changes brought by the pandemic continue to persist. As reported by Audimob in the 18-th report on the mobility of Italians of 2021 (Istituto Superiore di Formazione e Ricerca per i Trasporti, 2021), the citizens are still less predisposed to utilize the public transport, specially in the case of buses. On the other hand during the investigation almost 35% of the respondents declared that will increase the number of travels on foot, 15% stated the same in the case of travels by bicycles and 8,8% in the case of the cars. Besides, according to the Smart Working Observatory of the Polytechnic of Milan, in the last trimester of 2021 the number of smart workers was around 4 millions, way higher if compared to the 570000 of 2019. In particular, referring to the Veneto region, where the city of Padova is located, the number of citizens that in 2021 declared to move 5 days a week to reach their job was 68.1%, 11.9% less if compared to the situation in 2019 (Veneto Region, 2021). This must be considered in the analysis of the mobility since there is a correlation between work from home and various transportation issues such as changing commuting patterns and decreased congestion, motorized trips, and emissions (Kong et al., 2022).

In this work we will investigate which are the effects that all these factors might have on the sustainable mobility, utilizing the bike sharing of Padova as case study. In order to do this we looked for answers to the following questions: Has the pandemic had a long term impact on bike sharing systems? How did the users behaviour mutated over time? How did micro-mobility changed from a temporal and a spatial-temporal perspective? Our analysis revealed that after the emergency period there's a greater predisposition of people to use the bike-sharing services, both as primary means of transport and during the free time. From the study of the rides network it emerged not only a general increase in the traffic volume but also a growth of the system connectivity, indicating that users now tend to explore new routes and areas of the city.

2. Previous Works

COVID-19 pandemic was a global phenomenon that affected the lives of everyone around the globe. For this reason, all its aspects were investigated by the scientific community. In particular, in this paper we are going to focus on the works that studied the effects of the pandemic on mobility. Analysing and understanding these effects is crucial to enhance the future urban planning and to move in the direction of a more sustainable mobility. The impact of the restriction policies on mobility and Covid-19 cases was analysed by Wellenius et al. (2021) and by Lane et al. (2022). These studies found out that the distancing policies were effective in the reduction of the general mobility and that the decrease of mobility had a strong correlation with a significant reduction of the cases of infections.

The social distancing policies had also the secondary effect of increasing the importance of telework, teleconferencing, online learning, telehealth, and online shopping. Mouratidis and Papagiannakis (2021) named this phenomenon as "virtual mobility" and stated that this could have an impact on urban mobility also during the post-pandemic era. The correlation between severity of the pandemic, mobility changes and lockdown measures was explored by Rahman et al. (2020), by Astroza et al. (2020) in the specific case of Santiago de Chile, and by Heiler et al. (2020) with mobile phone data.

In Italy, Beria and Lunkar (2020) focused on the movement of the population just before the lockdown and on the mobility of the people during the lockdown. The impact of Covid-19 on modal preference of commuters was investigated in India by Pawar et al. (2020) and in Budapest by Bucsky (2020). From this second study it emerged that in the city of Budapest during the pandemic the public transport demand decreased by 80%, while in case of cycling and bike sharing the decrease was way lower (respectively 23% and 2%). The resilience of bikes and bike sharing systems is highlighted also by the works of Buehler and Pucher (2021), Campisi et al. (2020), and Filipe Teixeira et al. (2022) who showed that cycling significantly increased from 2019 and 2020 in Europe, USA and Australia and that during the pandemic bike-sharing systems were able to substitute public transport and had a major impact with respect to e-scooter sharing. Padmanabhan et al. (2021) found out that the bike sharing systems of New York, Boston and Chicago were negatively impacted during the pandemic in terms of the number of rides, fact explained with the diffusion of work from home. On the other side they noticed an increase in the average duration of the trips. A similar conclusion is valid for London (Heydari et al., 2021) and Zurich (Li et al., 2021b). The drastic increase of hire time is explained by the authors with a shift from public transport. A deeper analysis of the New York case study, with a particular focus on the relationship between bike sharing and public transport, can be found in the works of Pase et al. (2020), Teixeira and Lopes (2020), and Bi et al. (2022).

From most of the studies that correlate pandemic and bike sharing it emerges that this last one has been fundamental to substitute public transport and has demonstrated its resilience. Considering also the contribution that micro-mobility services gives in alleviating traffic congestion and transport emission (Li et al., 2021a) (Zhang and Mi, 2018), it becomes clear that is crucial to understand what politics can do to promote its diffusion. For this reason many studies concentrated on this topic. In particular Barbarossa (2020) analyzed 10 local Italian government policies concerning post-pandemic sustainable mobility in order to evaluate the effectiveness of the ongoing actions in shaping future urban mobility. The successes and the failures of anti-COVID cycling-friendly initiatives globally introduced were analyzed by Nikitas et al. (2021). In Germany, Schmidt et al. (2021) suggested that Covid-19 can be seen as a window of opportunities to move towards a more sustainable world and stressed the importance of personal norms to guide us in this direction. The degree of commitment of people to more sustainable transport policies options was investigated in Spain (Awad-Núñez et al., 2021). The study found that after the pandemic the idea of major car restrictions, enlargement of pedestrian spaces, and a switch to more sustainable mobility, is well accepted if compared to what would be observed under normal circumstances. According to Wang and Sun (2022) effective market supervision is also a necessary premise in order to obtain the environmental benefits we are seeking for.

To be best of our knowledge, even if a lot research works focused on the comparison between the pandemic and the pre-pandemic habits of urban mobility, very few papers investigated what actually happened after the emergency period. Understanding the actual situation of Bike Sharing Systems is crucial to improve the urban planning and, as a consequence, to turn this pandemic into an opportunity to make our cities more sustainable. For this reason in this paper we decided to address the problem of understanding how the micro urban mobility has changed after the pandemic and how the behaviour of the population has mutated.

3. Dataset

In this paper, we use the data of the free-floating bike-sharing service of Padova as a case study. This data, provided by the Municipality of the city, has been collected and anonymized. We collected a dataset over a period of three years, from May 2019 till May 2022. In this dataset, each record represents a ride and it contains the information about: the starting coordinates, starting time, ending coordinates, ending time, anonymized user-id, subscription type, bike-id and bike type. For each record we also computed the two following metrics:

- Rides Duration: expressed in minutes and obtained from the difference of ending and starting time.
- Travelled Distance: computed with the geodesic distance formula applied to ending and starting coordinates.

We pre-processed the data in order to remove corrupted records: in particular we removed all records that did not contain all the information about the starting/ending coordinates and time. We also deleted all the records whose coordinates were not consistent with the map of Padova. In particular each item that had the starting and/or the ending coordinates out of the boundaries was removed. At the end of the pre-processing we ended up having 979756 items in our dataset. Besides a meteorological dataset of the city of Padova was retrieve from the Arpav website (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto). The dataset contained hourly information about both the temperature and the precipitations in the city. These information were integrated in the rides dataset during part of the analysis.

4. Analytical Methods

How did the pandemic changed our way to utilize the bike sharing service? This is the main question our study wants to find an answer to. In this section we are going to describe the approach and the methods utilized to address this question.

4.1. Time Intervals Subdivision

We decided to perform the analyses on three different periods of 9 weeks each, around the months of October and November of 2019, 2020 and 2021. The considered periods are the following:

- Pre-Pandemic: from 2019-09-30 to 2019-12-02.
- Pandemic: from 2020-10-05 to 2020-12-07.
- Post-Panemic: from 2021-10-04 to 2021-12-06

We have chosen these particular periods in order to minimize the influence that holidays might have. In fact in October all the commercial activities are yet at full capacity after the summer. Besides the university starts at the beginning of October. This is crucial since the university of Padova hosts around 60000 students that have certainly a huge impact in the market of bike sharing. In fact sharing mobility users under 45 in Italy represents the 80% of the market (Istituto Superiore di Formazione e Ricerca per i Trasporti, 2020). These three time intervals are considered representative of a Pre-Pandemic, Pandemic and Post-Pandemic World. In particular we can consider the period of October-November 2020 as a full Pandemic period, since at that time the trend of infections had undergone a rapid surge and for this reason the 13 and 18 of October two Decree-Laws were issued in order to contain the virus.

4.2. Users Classification

In order to deeply understand the changes in the users behaviours we identified two users categories:

- Regular: Performed at least 7 rides in the considered period
- Occasional: Performed less then 7 rides in the considered period

By doing this subdivision we are able to understand if and how the pandemic might have impacted different types of users differently. The threshold value 7 was chosen by assuming that a regular user rents a bike at least once per week, with at most 2 weeks with no rides (in a 9-week period). However, we experimentally observed that similar results appear even with slightly different thresholds. Regular Users utilize the service with a certain regularity. We can suppose that they use bikes as a transportation medium to reach their work, university, gym, etc. On the other hand it's likely that most Occasional Users are tourist visiting the city, new people that decide to try the service or people that use it only when needed for particular occasions. The distinction between the two user categories and the three identified pre-pandemic, pandemic and post pandemic periods is the common thread in most of our experiments.

4.3. Spatial Network Analysis

In order to capture spatial-temporal changes, it was necessary to introduce a spatial subdivision of the city. In particular we divided Padova with a grid of 399 squares, that cover the entire area allowed by the bike-sharing system provider. The grid is a rectangle composed by 19*21 squares, each of side 500 meters.

In order to detect interesting patterns in the bike-sharing usage we also modeled the map/grid as a graph where each square corresponds to a node. A weighted graph G is defined by its set of vertices $\mathcal{V}$, its set of edges $\mathcal{E} = \mathcal{V} * \mathcal{V}$, and by a weighting function $\rho : \mathcal{E} \rightarrow \mathbb{R}$ that indicates the number of rides between two areas of the grid. The number of nodes and the number of edges are indicated respectively as $V = |\mathcal{V}|$ and $E = |\mathcal{E}|$. If two areas are not connected by any ride the edge linking them is going to have weight of 0.

We can now define the weighted adjacency matrix $\mathbf{W} \in \mathbb{R}^{V \times V}$, where $W_{ij} = \rho_{ij} \geq 0$ is the weight of the edge linking nodes i and j. The unweighted degree of a node is defined as the number of other nodes is connected to by an edge, $\delta_i = \Sigma_{j=1}^{V} I(\rho_{ij} \geq 1)$ where $I(\cdot)$ is equal to 1 if the condition is satisfied and 0 otherwise. The weighted degree of a node i can be defined as $d_i = \Sigma_{j=1}^{V} \mathbf{W}_{ij}$. For simplicity in this paper we will indicate the unweighted and weighted degree of a node respectively as its degree and its heat.

Finally, to analyze the connectivity of the graph we need to introduce the concepts of Local Clustering Coefficient (LCC) and Average Node Connectivity (ANC). The LCC it's a way to measure how strongly the neighbors of a considered node are connected to each other. Given the node i, its local clustering coefficient is computed as:

$$\gamma_i = \frac{2|e_{jk} : j, k \in N_i, e_{jk} \in \mathcal{E}|}{\delta_i(\delta_i - 1)}$$

where N_i is the set of neighbors of node i and $\delta_i = |N_i|$. We can have a general idea of the local connectivity by computing its mean on all the nodes of the graph:

$$\bar{\gamma} = \frac{1}{V} \sum_{j=1}^{V} \gamma_i(t)$$

The ANC was first defined in (Beineke et al., 2002) and represents the average number of nodes that must be removed from the graph in order to disconnect a randomly selected pair of nonadjacent nodes. It can be computed as

$$\bar{\kappa}(G) = \frac{\sum_{u,v} \kappa_G(u, v)}{\binom{V}{2}}$$

where $\kappa_G(u, v)$ is the maximum number of disjoint paths between the nodes u and v. The defined measures of heat, degree, LCC and ANC were already widely used in literature to study these types of networks (Xu et al., 2020; Pase et al., 2020; Li et al., 2021b; Wu and Kim, 2020) and will be later utilized in the results section to analyse the rides graph characteristics and connectivity.

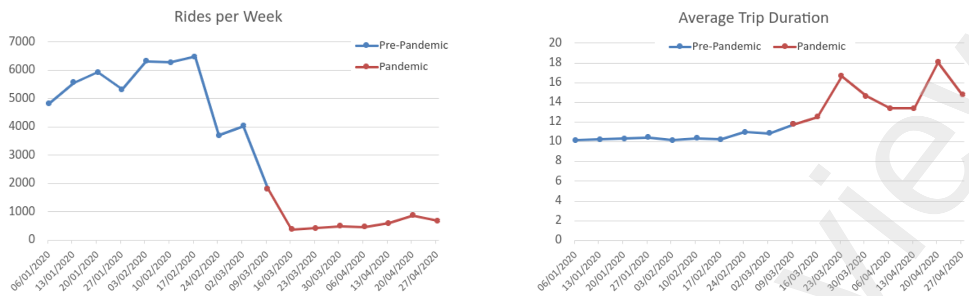
5. Results and Discussion

In this section we are going to present the results of the analysis performed on the bike-sharing data. The first subsection (5.1) briefly describes the moment when the pandemic exploded. The main analysis is concentrated in the second and third subsections, whose purpose is to highlight the long terms effects of the pandemic respectively from a temporal (5.2) and spatial-temporal perspectives (5.3).

5.1. Outbreak of the pandemic

In order to understand the long terms effect of the pandemic it's useful to first analyse what happened during the emergency period. The Veneto region, and in particular the Padova district, was one of first areas in Italy to be reached by the virus. For this reason in Veneto all schools closed yet on the February 23. On March 9 the Italian Government decided to ban all "non-essential" travels throughout all the Italian territory, and on March 11, the lockdown officially started.

Figure 1 (a) shows the number of rides per week starting from the January 6 to May 3, 2020. It's clear that already from the last week of February, when the schools closed in the region, the number of weekly rides quickly dropped (from around 6500 to about 4000). After two other weeks the number of rides didn't even reach one thousand and remained that low throughout the all lockdown. This trend is in line with the general drop of the mobility in that period. With respect to the first months of 2020 the general number of travels and the number of people moving dropped respectively by 65% and



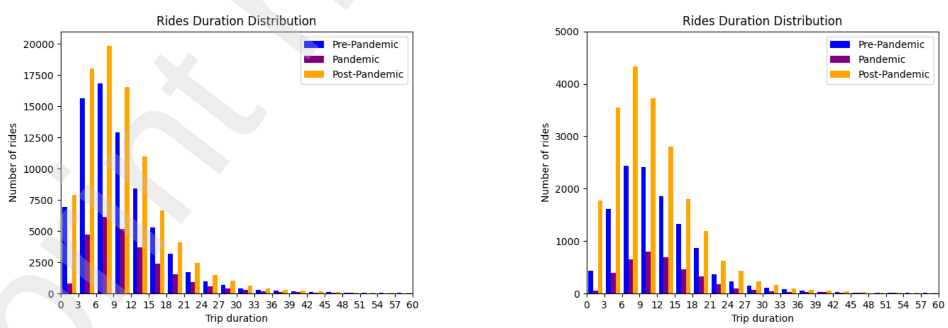
(a) (b)

Figure 1: These Graphs represent respectively the Number of Weekly Rides and the Average Trips Duration (in minutes) in the two months before Covid-19 and during the lockdown period.

80% (Istituto Superiore di Formazione e Ricerca per i Trasporti, 2020). In Figure 1 (b) it's possible to see the trend of the average trip duration. The plot clearly indicates that on average the trips duration has increased during the pandemic. Similar results were observed in Pase et al. (2020) for New York and in Li et al. (2021b) for Zurich.

5.2. A temporal analysis of Pre and Post Pandemic

In the previous section we reported the mobility pattern during the lockdown and the first phases of the pandemic. As expected, there was a huge drop of rides. In this section, we want to expand the analysis and to consider also the post-pandemic conduct on the mobility.

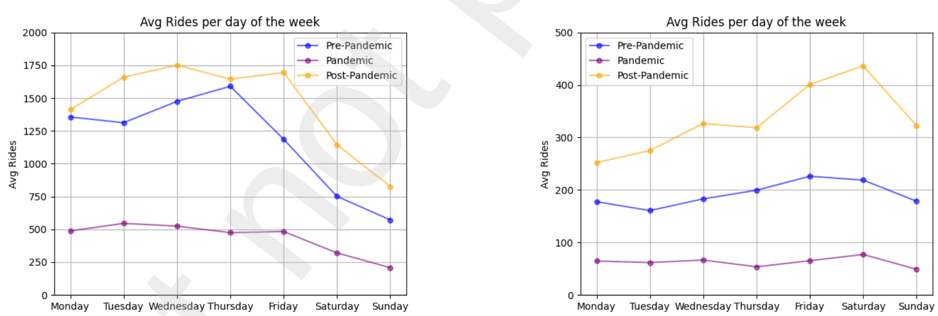


(a) Regular Users (b) Occasional Users

Figure 2: Rides Duration Distribution for Regular and Occasional Users in the three periods Pre-Pandemic, Pandemic and Post-Pandemic.

In order to investigate how the habits of the regular and occasional users have changed, we decided to answer the following questions: Were there any changes in the rides duration? When do users utilize the most the service? How much do weather conditions influence the bikes usage? Did this changed over time?

To tackle the first question we considered the ride duration distribution for both regular and occasional users. We computed the distribution by binning the trip duration into intervals of 3 minutes and for each time-window we summed all the rides that last in that amount of time, as shown in Figure 2. In the graphs are shown only rides that last within an hour since the number of longer rides is negligible. In the case of Regular users the peak is between 6 - 9 minutes in all the considered periods. This observation does not apply in the case of Occasional Users, where the peak during the pandemic was in the interval of 9 - 12 minutes, in line with what we observed in Figure 1 (b). Altogether the distribution before and after the pandemic remained unchanged except for very short rides (0 - 3 minutes). In this case in fact the number of short rides in proportion seems to have decreased after the pandemic in the case of Regular Users, but increased in the case of Occasional Users.

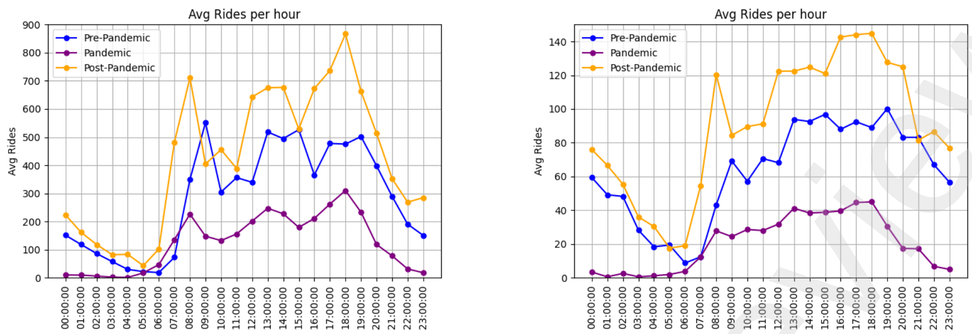


(a) Regular Users

(b) Occasional Users

Figure 3: Number of rides per day of the week for Regular and Occasional Users in the three periods of Pre-Pandemic, Pandemic and Post-Pandemic.

To identify when the service is used the most and whether this has changed over time, we focus on two main factors: what are the peak times during the day and what are the peak days during the week. To answer these questions we averaged on the three different period the numbers of rides per day of the week and the number of rides per week in the different hours of the day. The



(a) Regular Users

(b) Occasional Users

Figure 4: Weekly Average rides per hour of the day for Regular and Occasional Users in the three periods Pre-Pandemic, Pandemic and Post-Pandemic.

results of these computations are presented respectively in Figure 3 and Figure 4. The behaviour of regular and occasional users are represented in distinct plots. From Figure 3 we can notice that in Post-Pandemic, the number of rides incremented also with respect to Pre-Pandemic for both types of users. The increment in the case of Occasional Users it's particularly pronounced, specially during Saturdays. Regular users in all considered cases utilize bikes more on the working week with respect to the weekend. However, in Pre-Pandemic period the peak was on Thursday, while in the Post-Pandemic period the number of rides remains high in almost all working week days.

The average number of rides per hours of the day is shown in Figure 4. At first we can notice that the Pandemic seems to have changed the users routine. In particular, in the case of regular users, the main peak of the day in the Pre-Pandemic period was between 9 and 10 a.m.. During the pandemic the morning peak has shifted to the window 8 to 9 a.m. and remained unaltered also in the Post-Pandemic period. The main peaks in the case of the Pandemic and Post-Pandemic periods are both represented by the time slot 6 to 7 p.m.. This didn't stand for the Pre-Pandemic where the afternoon rides were almost equally distributed from 5 to 8 p.m.. Occasional Users tend to have less regular hours if compared to the Regular ones and to be more active at night both during the Pre and Post-Pandemic periods. This wasn't the case during the pandemic, since there were basically no rides during the night.

Finally we were interested to measure whether the attitude of people was changed with respect to the weather conditions. In order to do this we

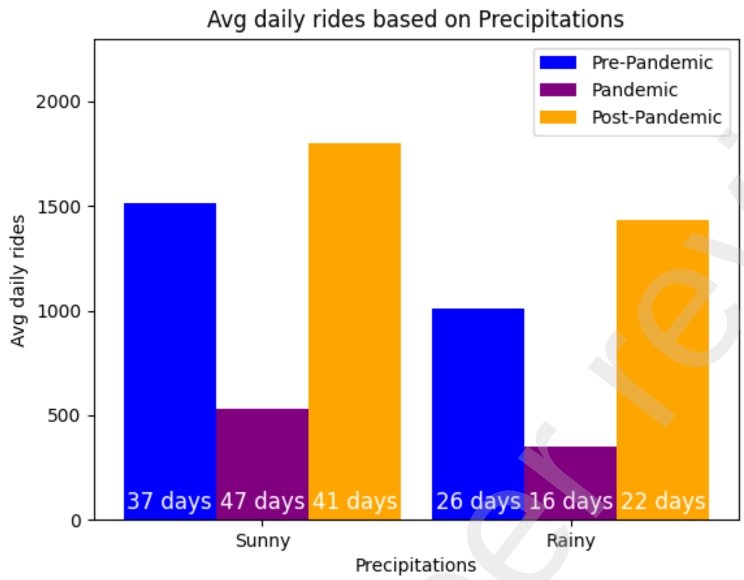


Figure 5: Average daily rides in the Sunny and Rainy days. The number of days over which the average was computed are indicated inside the bars.

exploited the precipitation data of the meteorological dataset. All days in the three considered periods were divided in two categories:

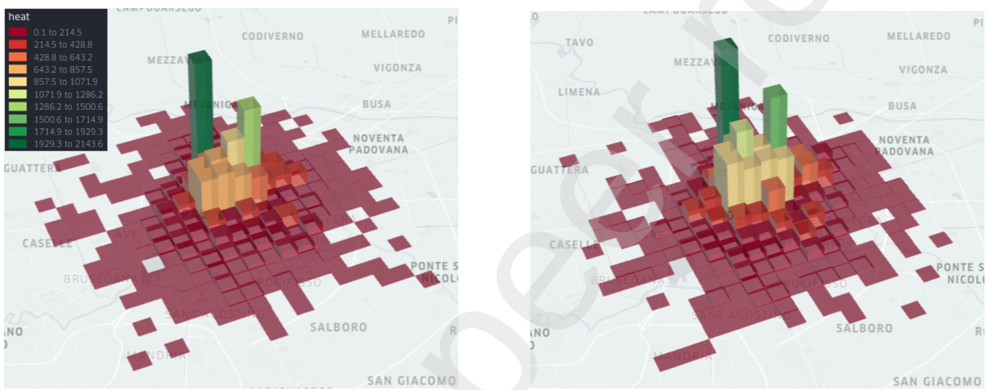
- Sunny: if there were 0mm of precipitation during the day (6 a.m.- 12 midnight).
- Rainy: if there were >0mm of precipitation during the day (6 a.m.- 12 midnight).

The choice of removing 6 hours during the night was dictated by the fact that in that period of time the number of rides is usually negligible, but a single hour of rain in that slot could have determined the classification of the day as Rainy. For each day in the three different periods we computed the total number of rides in the considered time-slot. This number was then mediated both for the days in the Sunny and Rainy categories.

The results obtained are shown in Figure 5. What we can notice is that if during the Pre-Pandemic period a rainy day resulted in a 33% reduction of the number of rides. This percentage reduced to 20% in the Post-Pandemic era. This clearly indicates a predisposition of the users to utilize the service also when the weather conditions are not ideal.

5.3. A spatial-temporal analysis of Pre and Post Pandemic

In this section we investigate how micro-mobility changed from a spatial-temporal perspective. As introduced in the Analytical Methods section, in order to performed this type of analysis we had to create a grid of the city from which we derived a graph G. The main metrics of the graph were then explored in order to identify changes in the users behavior.

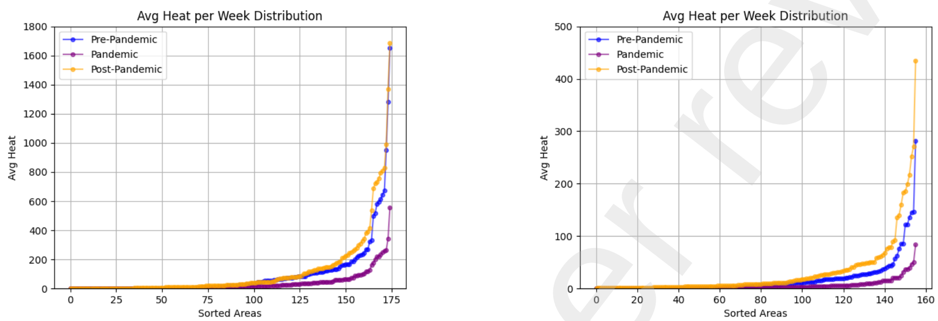


(a) 2019 Pre-Pandemic (b) 2021 Post-Pandemic

Figure 6: Average week heat for each area in Pre-Pandemic (2019) and Post-Pandemic (2021).

The first parameter we took into consideration is the heat and how it is distributed on the map. Recall that the heat of an area is the number of rides that start or end in that area. In particular in Figure 6 we represent the heat map of the city in the Pre-Pandemic and Post-Pandemic periods. For each area we calculated the average heat per week. We removed from the map all the squares with heat = 0, i.e. the ones that in that particular period weren't touched by any ride. As it's possible to see, most of the traffic is concentrated in the city center. The two principal peaks, in dark and light green, are the same in the two considered periods and represent respectively the train station and a university area. In particular, in the case of the train station, the two peaks were respectively of 1941.8 rides in the case of the Pre-Pandemic period (2019) and 2143.5 rides in the case of Post-Pandemic (2021).

After the pandemic we can notice a general increment of the heat values both in the central and peripheral areas, if compared with the situation in the Pre-Pandemic period. The increment of the heat in the city center can be easily explained with a general volume growth in terms of number of rides. In the case of the periphery this seems to indicate a greater predisposition of users to travel longer distances with respect to the Pre-pandemic era.



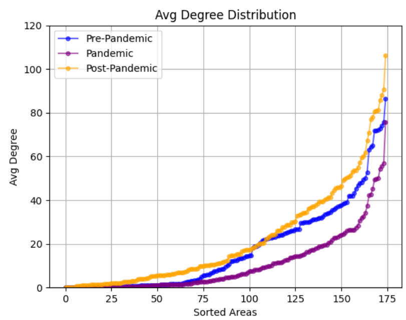
(a) Regular (b) Occasional

Figure 7: Weekly average heat for each area in the case of Regular and Occasional Users in the Pre-Pandemic, Pandemic and Post-Pandemic periods.

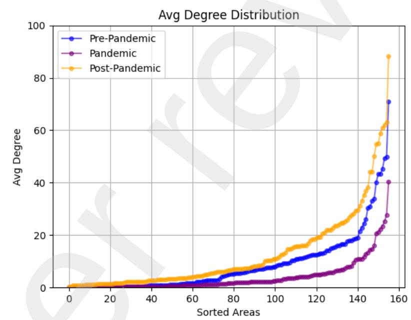
The heat was deeper investigated to better identify other possible new patterns in the users behaviour. In order to do this we sorted the nodes in the map according to their heat, in each of the three periods of Pre-Pandemic, Pandemic and Post-Pandemic. The outcome distribution of the nodes is represented in Figure 7. We decided to remove from the figure all the nodes that didn't reached 10 rides in at least one of the considered periods.

We notice that the majority of the rides are performed by regular users in the considered periods. For both occasional and regular users, the Post-Pandemic curve is above the ones of Pre-Pandemic and Pandemic. This confirms that the increment on mobility is distributed all over the city, and not just on few areas. In particular, in the case of occasional users the difference between Pre-Pandemic and Post-Pandemic is more significant. This could indicate a greater predisposition of users to use the bike also in their free time.

The heat can be used to quantify the flow in the map, however it does not detect interesting patterns of usage. To better understand how the user behaviour has changed, we analyse the graph using the metrics of degree, Local Clustering Coefficient (LCC), and Average Node Connectivity (ANC) in order to understand how its connectivity has changed. The results of this analysis are described in the following. First we computed the weekly average degree of the nodes in the three periods of interest. The degree distribution graphs, for the regular and occasional users, are shown in Figure 8. The considered nodes have been selected and ordered in the same way as in Figure 7.



(a) Regular



(b) Occasional

Figure 8: Weekly average degree for each area in the case of Regular and Occasional Users in the three periods Pre-Pandemic, Pandemic and Post-Pandemic.

The general increase of the average degree in the Post-Pandemic period with respect to the Pre-Pandemic is clearly evident. This indicates that not only the number of rides has increased, but also the number of different routes taken by the users. This is true for both cases of regular and occasional users.

A deeper network analysis was finally performed by investigating the Local Clustering Coefficient (LCC), and Average Node Connectivity (ANC). The values of the LCC of the nodes can be observed in Figure 9.

In particular we plotted only the nodes whose LCC values were different from 0 in at least of the three periods. Moreover, for each period the nodes are sorted in ascending order according to their LCC values. Recall that the Local Clustering Coefficient measures how strongly the neighbors of a node are connected to each other. From the Figure we can immediately notice that the Post-Pandemic curve is again above the Pre-Pandemic one for most of the values. This is also confirmed if we compute the averages LCC values over the entire map/graph, which are respectively: 0.60 for the Pre-Pandemic, 0.49 for the Pandemic, and 0.67 for the Post-Pandemic. Similar results are obtained in the case of the Average Node Connectivity (ANC), whose average values in the three periods are respectively: 4.49, 2.96, and 7.27. From this

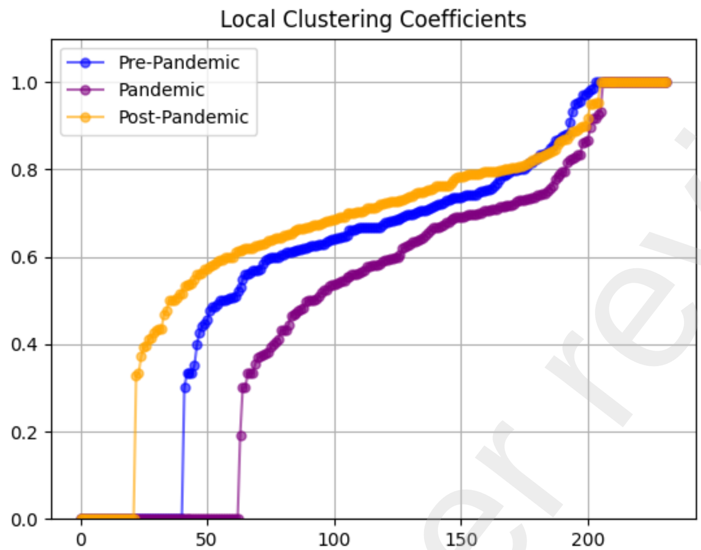


Figure 9: Local Clustering Coefficient of non-isolated nodes in Pre-Pandemic, Pandemic, Post-Pandemic periods.

analysis it's clear that the graph connectivity significantly improved after the pandemic, even if compared to the pre-pandemic situation. This confirms the general behaviour of the users in the post-pandemic phase to explore more areas and more routes of the city using the bike-sharing system.

6. Conclusions

In this paper we have studied the free-floating bike sharing system of the city of Padova, and we compared the user behaviour before and after the Pandemic.

In the proposed analysis we have observed a general increase of the free-floating bike sharing service. We have seen an increase of the total amount of rides, as well an expansion of the service towards more peripheral areas. In the case of occasional users the difference between Pre-Pandemic and Post-Pandemic is more significant. This could indicate a greater predisposition of users to use the bike also in their free time. In the Post-Pandemic period we observe a propensity of the users to utilize the service also when the weather conditions are not ideal. The increment of rides is spread all over the map, this seems to indicate a greater predisposition of users to travel longer distances with respect to the Pre-pandemic era. From the analysis of routes and the graph connectivity, we observe a significant improvement of the Local Clustering Coefficient and Average Node Connectivity after the pandemic. This confirms the general behaviour of the users, in the post-pandemic phase, to explore more areas and more routes of the city using the bike-sharing system.

We conjecture that these new behaviours can in part be explained with a different life-style developed during the pandemic: restrictions have stimulated the population to use non collective transportation means; at the same time, a more responsible and environmental-friendly attitude has stimulated the use of bikes and other light means (e.g., scooter). There are no clear causality relations among these changes, but we believe they positively reinforce each other.

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References

Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto, . URL: https://www.arpa.veneto.it/.

Astroza, S., Tirachini, A., Hurtubia, R., Carrasco, J., Guevara, A., Munizaga, M., Figueroa, M., 2020. Mobility changes, teleworking, and remote communication during the covid-19 pandemic in chile. Transport Findings doi:10.32866/001c.13489.

Awad-Núñez, S., Julio, R., Moya-Gómez, B., Gomez, J., Sastre González, J., 2021. Acceptability of sustainable mobility policies under a post-covid-19 scenario. evidence from spain. Transport Policy 106, 205–214. doi:https://doi.org/10.1016/j.tranpol.2021.04.010.

Barbarossa, L., 2020. The post pandemic city: Challenges and opportunities for a non-motorized urban environment. an overview of italian cases. Sustainability 12. doi:10.3390/su12177172.

Beineke, L.W., Oellermann, O.R., Pippert, R.E., 2002. The average connectivity of a graph. Discrete Mathematics 252, 31–45. doi:https://doi.org/10.1016/S0012-365X(01)00180-7.

Beria, P., Lunkar, V., 2020. Presence and mobility of the population during covid-19 outbreak and lockdown in italy. Sustainable Cities and Society 65. doi:10.1016/j.scs.2020.102616.

Bi, H., Ye, Z., Zhang, Y., Zhu, H., 2022. A long-term perspective on the covid-19: The bike sharing system resilience under the epidemic environment. Journal of Transport and Health 26, 101460. doi:https://doi.org/10.1016/j.jth.2022.101460.

Bucsky, P., 2020. Modal share changes due to covid-19: The case of budapest. Transportation Research Interdisciplinary Perspectives 8, 100141. doi:https://doi.org/10.1016/j.trip.2020.100141.

Buehler, R., Pucher, J., 2021. Covid-19 impacts on cycling, 2019–2020. Transport Reviews 41, 393–400. doi:10.1080/01441647.2021.1914900, arXiv:https://doi.org/10.1080/01441647.2021.1914900.

Campisi, T., Basbas, S., Skoufas, A., Akgün, N., Ticali, D., Tesoriere, G., 2020. The impact of covid-19 pandemic on the resilience of sustainable mobility in sicily. Sustainability 12. doi:10.3390/su12218829.

Filipe Teixeira, J., Silva, C., Moura e Sá, F., 2022. The role of bike sharing during the coronavirus pandemic: An analysis of the mobility patterns and perceptions of lisbon's gira users. Transportation Research Part A: Policy and Practice 159, 17–34. doi:https://doi.org/10.1016/j.tra.2022.03.018.

Heiler, G., Reisch, T., Hurt, J., Forghani, M., Omani, A., Hanbury, A., Karimipour, F., 2020. Country-wide mobility changes observed using mobile phone data during covid-19 pandemic, in: 2020 IEEE International Conference on Big Data (Big Data), pp. 3123–3132. doi:10.1109/BigData50022.2020.9378374.

Heydari, S., Konstantinoudis, G., Behsoodi, A.W., 2021. Effect of the covid-19 pandemic on bike-sharing demand and hire time: Evidence from santander cycles in london. PLOS ONE 16, 1–16. doi:10.1371/journal.pone.0260969.

Istituto Superiore di Formazione e Ricerca per i Trasporti, 2020. 17° report on italians mobility. URL: https://www.isfort.it/wp-content/uploads/2020/12/RapportoMobilita2020.pdf.

Istituto Superiore di Formazione e Ricerca per i Trasporti, 2021. 18° report on italians mobility. URL: https://www.isfort.it/wp-content/uploads/2021/11/211130_RapportoMobilita2021.pdf.

Kong, X., Zhang, A., Xiao, X., Das, S., Zhang, Y., 2022. Work from home in the post-covid world. Case Studies on Transport Policy 10, 1118–1131. doi:https://doi.org/10.1016/j.cstp.2022.04.002.

Lane, H., Şahin, M., Otto, P., 2022. Mobility restrictions as a pandemic response. medRxiv doi:10.1101/2022.02.11.22270865.

Li, A., Gao, K., Zhao, P., Qu, X., Axhausen, K.W., 2021a. High-resolution assessment of environmental benefits of dockless bike-sharing systems based on transaction data. Journal of Cleaner Production 296, 126423. doi:https://doi.org/10.1016/j.jclepro.2021.126423.

Li, A., Zhao, P., Haitao, H., Mansourian, A., Axhausen, K.W., 2021b. How did micro-mobility change in response to covid-19 pandemic? a case study based on spatial-temporal-semantic analytics. Computers, Environment and Urban Systems 90, 101703. doi:https://doi.org/10.1016/j.compenvurbsys.2021.101703.

Mouratidis, K., Papagiannakis, A., 2021. Covid-19, internet, and mobility: The rise of telework, telehealth, e-learning, and e-shopping. Sustainable Cities and Society 74, 103182. doi:https://doi.org/10.1016/j.scs.2021.103182.

Nikitas, A., Tsigdinos, S., Karolemeas, C., Kourmpa, E., Bakogiannis, E., 2021. Cycling in the era of covid-19: Lessons learnt and best practice policy recommendations for a more bike-centric future. Sustainability 13. doi:10.3390/su13094620.

Padmanabhan, V., Penmetsa, P., Li, X., Dhondia, F., Dhondia, S., Parrish, A., 2021. Covid-19 effects on shared-biking in new york, boston, and chicago. Transportation Research Interdisciplinary Perspectives 9, 100282. doi:https://doi.org/10.1016/j.trip.2020.100282.

Pase, F., Chiariotti, F., Zanella, A., Zorzi, M., 2020. Bike sharing and urban mobility in a post-pandemic world. IEEE Access 8, 187291–187306. doi:10.1109/ACCESS.2020.3030841.

Pawar, D.S., Yadav, A.K., Akolekar, N., Velaga, N.R., 2020. Impact of physical distancing due to novel coronavirus (sars-cov-2) on daily travel for work during transition to lockdown. Transportation Research Interdisciplinary Perspectives 7, 100203. doi:https://doi.org/10.1016/j.trip.2020.100203.

Politis, I., Georgiadis, G., Papadopoulos, E., Fyrogenis, I., Nikolaidou, A., Kopsacheilis, A., Sdoukopoulos, A., Verani, E., 2021. Covid-19 lockdown measures and travel behavior: The case of thessaloniki, greece. Transportation Research Interdisciplinary Perspectives 10, 100345. doi:https://doi.org/10.1016/j.trip.2021.100345.

Rahman, M.M., Thill, J.C., Paul, K.C., 2020. Covid-19 pandemic severity, lockdown regimes, and people's mobility: Early evidence from 88 countries. Sustainability 12. doi:10.3390/su12219101.

Schmidt, K., Sieverding, T., Wallis, H., Matthies, E., 2021. Covid-19 – a window of opportunity for the transition toward sustainable mobility? Transportation Research Interdisciplinary Perspectives 10, 100374. doi:https://doi.org/10.1016/j.trip.2021.100374.

Teixeira, J.F., Lopes, M., 2020. The link between bike sharing and subway use during the covid-19 pandemic: The case-study of new york's citi bike. Transportation Research Interdisciplinary Perspectives 6, 100166. doi:https://doi.org/10.1016/j.trip.2020.100166.

Veneto Region, 2021. Statistics report 2021. URL: https://statistica.regione.veneto.it/Pubblicazioni/RapportoStatistico2021/index.html.

Wang, Y., Sun, S., 2022. Does large scale free-floating bike sharing really improve the sustainability of urban transportation? empirical evidence from beijing. Sustainable Cities and Society 76, 103533. doi:https://doi.org/10.1016/j.scs.2021.103533.

Wellenius, G.A., Vispute, S., Espinosa, V., et al., 2021. Impacts of social distancing policies on mobility and covid-19 case growth in the us. Nature communications doi:https://doi.org/10.1038/s41467-021-23404-5.

Wu, C., Kim, I., 2020. Analyzing the structural properties of bike-sharing networks: Evidence from the united states, canada, and china. Transportation Research Part A: Policy and Practice 140, 52–71. doi:https://doi.org/10.1016/j.tra.2020.07.018.

Xu, Z., Zhang, Q., Chen, D., He, Y., 2020. Characterizing the connectivity of railway networks. IEEE Transactions on Intelligent Transportation Systems 21, 1491–1502. doi:10.1109/TITS.2019.2909120.

Zhang, Y., Mi, Z., 2018. Environmental benefits of bike sharing: A big data-based analysis. Applied Energy 220, 296–301. doi:https://doi.org/10.1016/j.apenergy.2018.03.101.

Zheng, R., Xu, Y., Wang, W., Ning, G., Bi, Y., 2020. Spatial transmission of covid-19 via public and private transportation in china. Travel Medicine and Infectious Disease 34, 101626. doi:https://doi.org/10.1016/j.tmaid.2020.101626.