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Understanding the impacts of COVID-19 on bike-sharing travel behaviors: Insights from the literature and a case study in New York City, USA

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ABSTRACT

The post-coronavirus era is a long-lasting challenge, but also a window of opportunities to strengthen the role of bike-sharing in molding a resilient transportation system. However, few studies have attempted to holistically review the recent literature in the last four years. This study aims to identify emerging topics regarding the impact of COVID-19 on bike-sharing by systematically critiquing research published between 2020 and 2023. The review was complemented by a case study in New York (USA) to address a research gap identified by the review. Scientometric analysis was applied to demonstrate research frontiers. We constructed and visualized network maps that depict information on the citations and terms of the documents that frequently appear in the title, keywords, and abstract of each reviewed document. Next, a clustering-based procedure was developed to infer and compare the major trip purposes in different pandemic periods for the case study. The results reveal that emerging topics include infection risks, active travel, and modal substitution that were less discussed before the pandemic. The results of the case study show that both residential and work trips had experienced significant growth before and after the outbreak, while residential trips saw a slightly higher increase in terms of the number of commuters. Additionally, residential trips can partly replace work trips in most Manhattan communities during the pandemic, implying that people may become more dependent on bike-sharing when working from home is prioritized. This research provides new perspectives on the pandemic's impact on bike-sharing for researchers. Practitioners may use the tools to better understand how the pandemic may drive changes in travel behaviors and plan accordingly.

1. Introduction

Four years have passed since the discovery of the first confirmed case of severe acute respiratory syndrome coronavirus-2 (COVID-19) in late 2019. According to the latest statistics published by Ministry of Health Singapore (2023), the number of estimated infections was as high as 32,035 during the week of November 26 to December 2, 2023, 10,000 higher than the level of the previous week. Similarly, New York City, USA, reported a 30% increase in hospitalizations due to infections from new variants of COVID-19: HV.1, BA.2.86, and JN.1 (New York Post, 2023; The New York Times, 2023). Children and the elderly are once again the most vulnerable COVID-19 sufferers. Hospitalization rates in London, UK, also reached a new peak in recent months, compared to earlier warm seasons (The Weather Channel, 2023). These global metropolises are susceptible to COVID-19 due to populous settlements and a densely connected public transport network. For example, New York City has a multimodal public transport system consisting of 472 subway stations, 234 bus routes (The Metropolitan Transportation Authority, 2023), and over 1800 docked stations for shared bikes (New York City Comptroller, 2023). Urban mobility facilitates the transmission of airborne viruses. Although scientists have gained more knowledge about COVID-19 in recent years, the effectiveness of medical treatments is limited, as viral variants have been evolving rapidly. To curb the spread of infections, local authorities in many cities must quarantine infected regions and restrict urban mobility by shutting down or downgrading public transport services, which has been proven to be effective during the early days of the outbreaks in 2020.

Intermediate transit contingency measures affect economic activities, leading to enormous financial loss. The economic consequence of the lockdown in Wuhan, China, is estimated to be as much as $24 billion per month (You et al., 2020). In this context, emerging mobility options were recently introduced to serve as an important component in transit contingency plans. Before COVID-19, bike-sharing had already

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experienced a boom in more than 1000 cities due to its convenience and resilience. During the pandemic, it was an ideal alternative when other options for transportation were not available. In May 2023, the World Health Organization announced that COVID-19 was no longer an international public health emergency, signaling that the disease would become endemic. Bike-sharing ridership has been recovered and even rebounded over the pre-pandemic levels in numerous cities, as COVID-19 is no longer a global concern. Potential decrease-recover-rebound patterns in bike-sharing usage have attracted much attention from the academia. The last four years have witnessed markedly increased interest in the short- and long-term impact of the COVID-19 pandemic and (or) endemic on bike-sharing. Motivations or barriers to adopt bike-sharing during the pandemic are generally studies through questionnaire surveys. The spatiotemporal changing patterns of cycling activities are also explored, thanks to the free availability of trajectory data of cycling rides in a number of programs such as Citi Bike in New York City or other programs.

Despite growing interest in emerging micromobility during the pandemic, few studies have attempted to holistically review the recent literature published over the past four years. A comprehensive review based on a rigorous examination of the literature on bike-sharing during different periods can help foster a better understanding of how it contributes to urban transport efficiency. Ricci (2015), Si, Shi, Wu, Chen, and Zhao (2019) and Fishman, Washington, and Haworth (2013), among other scholars, have elegantly summarized various emerging topics of bike-sharing before the COVID-19 pandemic. The COVID-19 pandemic has affected how people work and travel: there is a rise in working from home and telecommuting. Therefore, there is a need to revisit the latest literature and identify new topics that evolve over time. This study aims to systematically review bike-sharing research published between 2020 and 2023, and the review is complemented by a case study in New York City, USA. The case study aims to verify whether the six ridership change patterns identified in the literature review are observable in New York City, while also remaining open to discovering new patterns or variations specific to this urban context. Building on this, the study serves one key purpose. It follows up on the broad trends identified in the scientometric review by providing a detailed, quantitative analysis of how these patterns manifest in a major urban center. This allows us to test the generalizability of the findings from the literature and potentially uncover nuances not captured in broader studies.

A method based on scientometric analysis was employed to identify research frontiers using network maps that contain information on document citations and key terms appearing in the title, keywords, and abstract of each reviewed document. The analysis aims at addressing two research questions about the literature.

1. What are the main multidisciplinary interests regarding bike sharing amid evolving COVID-19 situations?
2. Did bike sharing, as a new and sustainable public transport mode, gain increased and sustained demand during the worldwide health crisis?

The in-depth review reveals the paucity of research on the understanding of changes in the travel behavior of bike-sharing trips before and after the pandemic. In summary, the main objectives of this study are: (1) to summarize the bike-sharing studies published after 2020; (2) to highlight major research domains that are of immediate relevance to COVID-19; (3) to demonstrate whether the travel behaviors of bike-sharing users change significantly before and after the pandemic based on a case study in New York City. We hope to inform the transportation research community by presenting a holistic review and the latest findings on the impacts of COVID-19 on bike-sharing. To the best of our knowledge, this is the first study to combine a review of COVID-19 related bike-sharing research and a case-study approach. While many studies in our review relied on descriptive statistics, our case study employs a novel clustering-based approach to identify and statistically validate changes in trip purposes before and after the initial COVID-19 outbreak. This methodological contribution allows for a more rigorous examination of behavioral changes.

The rest of the paper is organized as follows. Section 2 describes the data and methods for the scientometric analysis and the case study. Section 3 presents an analysis of the most important papers, the clusters of research domains, and individual studies based on different bike-sharing programs. Section 4 discusses key findings from the case study. Section 5 concludes our discussions with a summary of future directions.

2. Methodology

Fig. 1 shows an overall roadmap that combines scientometric analysis and the exploration of changes in travel behaviors based on a case study. The scientometric analysis not only informs the bike-sharing research community with emerging domains, but also informs the identification of research questions for the case study. Section 2.1 outlines the steps and tools by which the scientometric analysis was carried out. Sections 2.2 and 2.3 explain the modeling and analytical parts of the case study, which is illustrated by a flowchart shown in Fig. 2.

2.1. Scientometric analysis

Scientometric analysis is a powerful tool for understanding state-of-the-art progress on topics of interest. It can pinpoint the most influential publications and potential clusters of knowledge domains given a database of literature. To conduct the analysis, a citation database was produced in the required format. We retrieved 110 papers from the Web of Science platform using a combination of the following string search: "TS = ((“bike sharing” OR “bicycle sharing” OR “shared bike*” OR “public bicycle*” OR “public bike*”) AND “COVID-19”)". The use of an asterisk (*) is to replace several characters in a word, so that the search may look for multiple words (e.g., bike* returns bike, bikes). These papers were published between 2020 and 2023 (with some online first papers that are supposed to be on a regular issue in 2024). These structured data sets were processed using CiteSpace, a scientometric analysis software. Although BibExcel, Ucinet, SCIMAT, and other programs have been developed, CiteSpace was chosen by this study due to its integration of the co-occurrence analysis of various topics such as authors, documents, institutions, and excellent visualization functions (Chen, 2015). While previous reviews using CiteSpace follow a standard research routine, this study focuses primarily on critical articles and emerging knowledge domains. Therefore, the analysis contains two scientometric techniques: (1) network analysis of document co-citation to visualize and identify important articles; and (2) cluster analysis of a network consisting of top terms that occur frequently in the title, keywords, and abstracts of each document.

2.2. Data and methods for the case study

2.2.1. Case study region and data processing

Citi Bike program in New York City is the main data source of our case study. New York City was selected based on a few considerations. First, the city is one of the metropolis in the USA that are hit severely by COVID-19. Second, its bike-sharing program remained fully operational during the course of the pandemic. Third, its timely release of high-quality bike-sharing data is highly appreciated. Citi Bike was launched in May 2013 and has nearly 1800 docked stations and more than 26,000 shared bikes. Fig. 3 shows the bike sharing stations that are currently operating and the boundaries of the communities defined by the New York City Planning Department. Data was collected from multiple data sources. Data on bike rental trips were downloaded from the official Citi Bike website (https://www.citibikenyc.com/). The original number of trips is 11,845,875 and reduced to 11,309,996

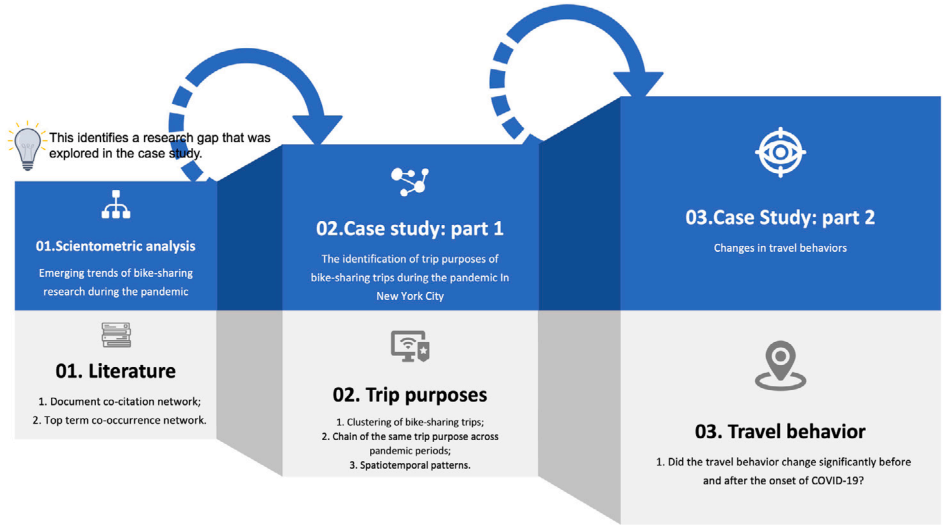

Fig. 1. An overall research pipeline of this study.

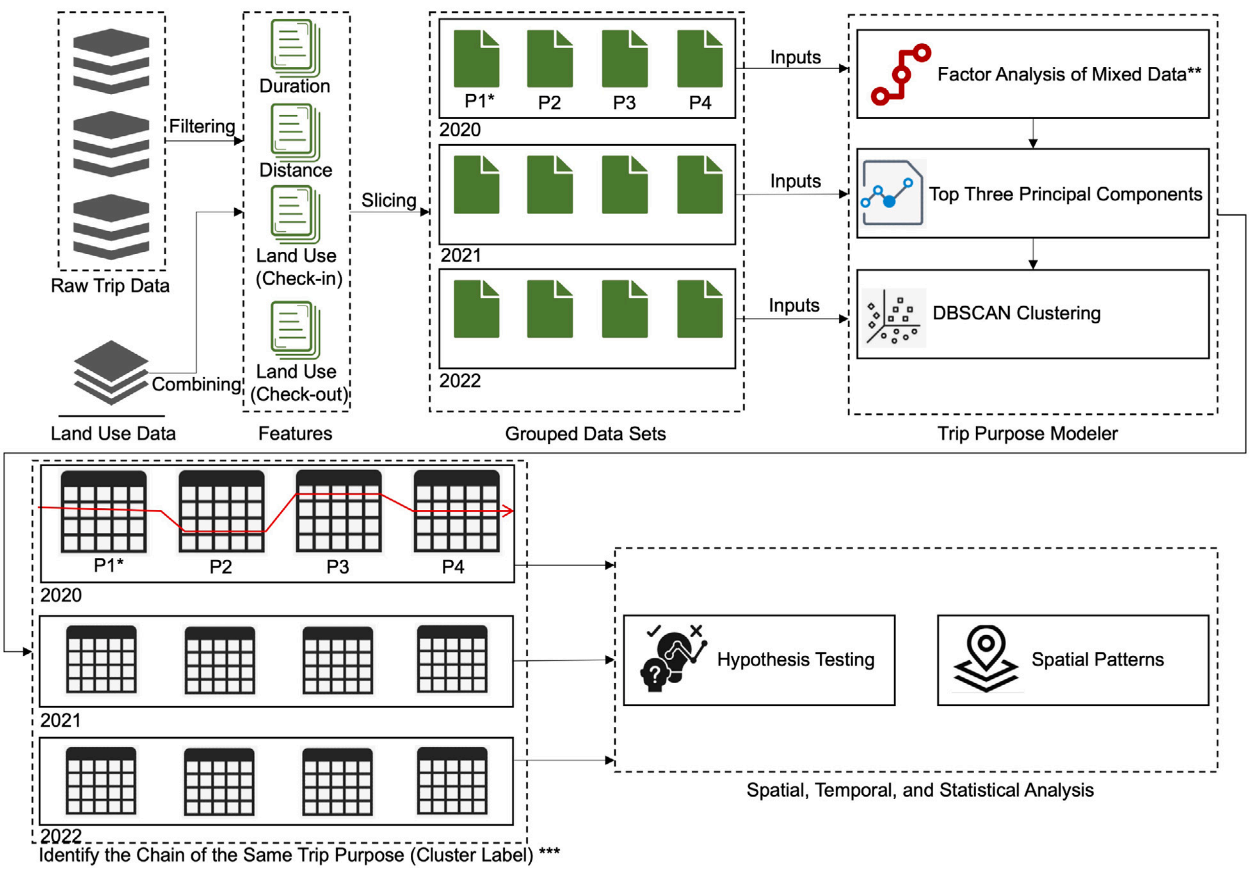

Fig. 2. A flowchart showing the data preprocessing, clustering modeling, and hypothesis testing of bike-sharing usage patterns in New York City in 2020, 2021, and 2022. *: P1, P1, P2, P4 denote the four periods corresponding to critical timelines of the pandemic development in the city (Table 1). **: Factor Analysis of Mixed Data works well with data of mixed types and is a generalized version of principal component analysis. ***: The vertical axis of each table represents cluster labels, and the horizontal axis represents the breakdown of trips by land use types at the origins and destinations. How to identify the chain of the same trip purpose across different periods in each year is illustrated in Section 4.2.1.

after the removal of the anomalous data. The NYC Planning provided geographical information on the boundaries of the community (https://zola.planning.nyc.gov/). ZOLA provides information on New York's land use types (https://zola.planning.nyc.gov/), which primarily include Commercial Districts, Manufacturing Districts, Residence Districts, Parks. Battery Park City, and PLAYGROUND. Major features of a trip include starting and ending geographical locations and station names, ride duration, and member type (subscribed or casual user). The trip features were combined with land use information for subsequent data modeling.

The bike-sharing trip data was pre-processed according to four criteria. Firstly, records with null and incomplete entries were removed.

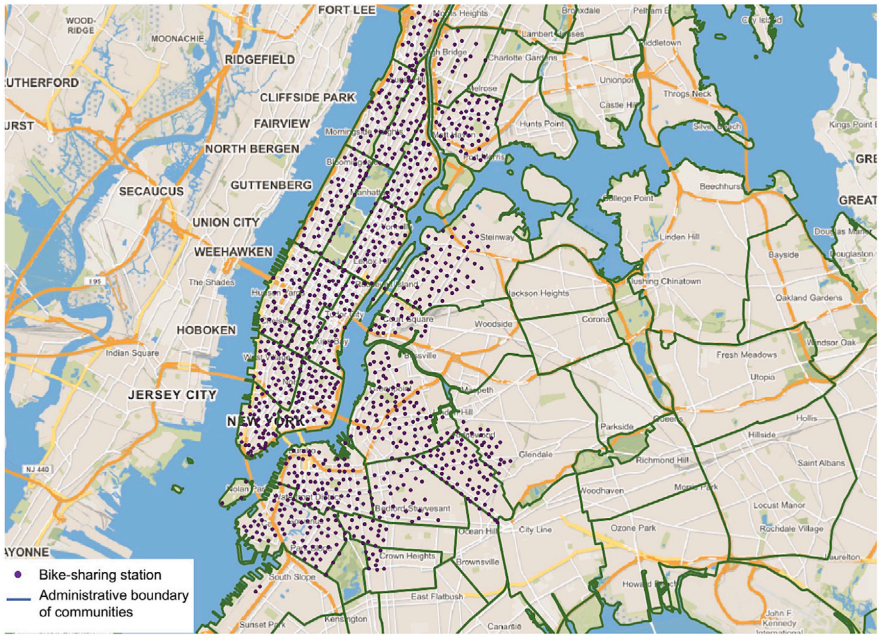

Fig. 3. Docked bikes-sharing stations in the City of New York, USA.

Second, a record was removed if its geographical locations were outside the study areas. Then, short trips with a duration less than 1 min or unreasonably long trips with a duration greater than 12 h were also excluded from the analysis. Lastly, all valid trips must have an average speed equal to or less than 30 km per hour. After generating a set of valid trips, several features for each trip were calculated, including the duration of the trip, the distance, the average speed and the types of land use at the departure and arrival bicycle station of the trip.

2.2.2. Clustering trip purposes in each period

Identifying bike-sharing trip purposes is the modeling part of the case study. Unlike survey-based approaches, the purpose of a trip must be inferred from the features of the trip. The objective was to identify groups of trips that share similar features but are different from those trips from another group, which can be efficiently modeled using unsupervised techniques such as clustering. Many clustering algorithms are developed, but this study selected Density-Based Spatial Clustering of Applications with Noise (DBSCAN) due to its ability to determine the number of clusters (Ester, Kriegel, Sander, Xu, et al., 1996). DBSCAN can detect clusters with a high density of data points and the clusters can be of any shape, whereas other algorithms such as K-Means can only work with convex clusters. However, DBSCAN is sensitive to the dimensions and data types of the input features. The raw feature table contains variables of numerical and categorical types, so traditional principal component analysis (PCA) does not support mixed data types. Consequently, mixed data factor analysis (FAMD) was used to reduce the dimension of the raw feature table (Halford, 0000). FAMD follows three steps to extract the main components. First, the numerical variables were standardized to ensure that the different variables were within the same scale. Second, categorical features (land use types) were also converted into binary variables via the one-hot encoding technique. To mitigate the issues of dominant binary variables, an encoded column m was divided by $\sqrt{\mu_m}$, which is calculated by

$$\mu_m = \frac{N_{ones}}{N} \tag{1}$$

where N_{ones} denotes the number of ones in the column, and N is the total number of rows. The result columns were also standardized to unify the data scale.

Lastly, all standardized variables were combined and fitted with a PCA algorithm. The algorithm extracted the top three principal components that can sufficiently explain the inertia of the data.

A processed table consisting of the main components for each trip was then sliced into four subtables that correspond to significant timelines of the initial evolution of COVID-19 in New York (Table 1). In period 1 there was no obvious community spread of the virus. The 16 March marked the beginning of the pandemic: the number of infections was on a sharp rise; the disease took a heavy toll on vulnerable populations; schools were closed; and people were advised against leaving their residences. The highest waves of infections started to taper off in period three, and the city gradually opened up in phases. Period 4 shows that the number of new cases levels off, indicating the disease became endemic after the initial outbreak.

Lastly, DBSCAN clustering was performed using each subtable. The algorithm assigned each trip a cluster label, but we still had to infer the meaning (trip purpose) of each label and the same trip purpose across different periods. A procedure was developed and illustrated with examples in Section 4.2.1.

2.3. Hypothesis testing

One main objective of this study was to demonstrate whether there exist significant changes in the bike-sharing trips before and after the initial pandemic in 2020. The same procedure was also applied to the data in 2021 and 2022 to observe whether the changes is short or long term. Because we already have good knowledge about major trip purposes across four periods, we can then compare the average percentage of a certain trip purpose in all communities in periods 1 and 2 using the Mann–Whitney U test.

The hypotheses are shown as follows.

- H_0: The proportion of trip purpose i in period 1 is equal to that in period 2;
- H_1 (lower-tailed test): The proportion of trip purpose i in period 1 is less than that in period 2; Or
- H_1 (upper-tailed test): The proportion of trip purpose i in period 1 is greater than that in period 2.

Table 1
Slices of the feature table in the pre-, during, and post-pandemic stages in 2021 in New York. Note that the feature tables in 2021 and 2022 were processed using the same cutoff dates below for a fair comparison. For example, period 1 in 2021 is from 2021/01/20 to 2021/03/16.

Duration	Start date	End date	Significant events
Period 1: Before the pandemic	2020/01/20	2020/03/16	March 1: First case in New York State March 14: First death case in New York State March 16: the closure of public schools
Period 2: Pandemic	2020/03/17	2020/05/01	March 22: The start of stay-at-home order April 6: The extension of stay-at-home order and public school closure
Period 3: After the pandemic	2020/05/02	2020/07/01	May 14: The extension of state of emergency for New York State June 8: The start of phase 1 opening June 22: The start of phase 2 opening
Period 4: Endemic	2020/07/02	2020/08/31	

Before actual computation, the data in a group were ranked in ascending order, and therefore each data point was assigned a rank. The test statistics were computed by the following equations:

$$U_1 = n_1 \times n_2 + \frac{n_1 \times (n_1 + 1)}{2} - R_1 \tag{2}$$

$$U_2 = n_1 \times n_2 + \frac{n_2 \times (n_2 + 1)}{2} - R_2 \tag{3}$$

where n_1 and n_2 is the number of days in period 1 and 2 respectively, R_1 and R_2 is the sum of the ranks for each group respectively. The test statistics U was the minimum of (U_1, U_2) and compared to the critical value based on the respective sample size to determine if the null hypothesis H_0 can be rejected at the given significance level.

3. The outcomes of scientometric analysis

3.1. Co-citation network

The co-citation network contains 252 nodes and 972 links which depict the connections of the articles cited by the 110 publications included in this study (Fig. 4(a)). Each node represents one document, and a link between two nodes is established if there is a citation between the two nodes. Because each document in the input database consists of full information regarding all the cited references, the number of nodes is higher than that of the originally searched articles. The purple-to-yellow color scale reflects different time slices (one slice per year), as shown in the legend. They also suggest that the majority of the citations occurred in 2022 and 2023 (greenish colors). Nodes with a pink ring are associated with a high betweenness centrality. Betweenness centrality measures how much influence a node has over the flow of information in a network and is employed to detect nodes that serve as a bridge between small communities in the graph. In bibliometric analysis, it is a useful technique to identify important publications that bridge different knowledge domains. The size of a node indicates the corresponding level of citations in the document. Intuitively, larger nodes means that the underlying documents can be considered important in the field of bike-sharing patterns during the pandemic. Tables 2 and 3 list the top ten articles according to the number of citations and betweenness centrality. Teixeira and Lopes (2020) has a network citation frequency of 47 and an overall frequency of 441 (Google Scholar), implying its importance in both the bike-sharing community and general transportation research fields. This study is among the first attempts to quantify the impact of COVID-19 on bike-sharing and the subway system. It was observed that bike sharing suffered less from the pandemic than subway and was therefore more resilient. Furthermore, it found that daily new incidents of COVID-19 in New York were negatively associated with the rate of ridership between the subway and Citi Bike, implying possible modal shifts from public transport to shared micromobility mode. The second and third ranked papers are also case studies. Nikiforiadis, Ayfantopoulou, and Stamelou (2020) administered surveys in a city in Greece to understand the perception of people about bike sharing in the context of the pandemic, while Hu, Xiong, Liu, and Zhang (2021) extracted patterns from the spatial traces of bike-sharing rides in Chicago. Survey responses and geospatial records of bike rides are two major data sources. The remaining seven papers are case studies in other major cities and were published during the early stages of the pandemic. These early investigations were quickly disseminated and referenced by subsequent research examining impacts in other cities.

While Table 2 presents significant papers within the field of bike-sharing, Table 3 shows the documents that are more interdisciplinary. Jenelius and Cebecauer (2020) obtained a centrality score of 0.24, indicating its appearance in many studies that focus on the different aspects of the impacts of COVID-19 on the general urban and transportation sectors. Other top papers in this table focus not only on the spatiotemporal dynamics of bike-sharing trips, also on the modal shift (Bucsky, 2020), the outlook of a nonmotorized society (Barbarossa, 2020), the effects of built environments and weather El-Assi, Salah Mahmoud, and Nurul Habib (2017), and other broader impacts of COVID-19.

The articles in bold appear in both tables, indicating that they attracted attention from scholars with active mobility, public transport, built environment, and other backgrounds. For example, Bucsky (2020) observed bike sharing started to replace short-distance bus trips after the pandemic worsened in Budapest, Hungary. Similar observations are also observed in Lisbon, Portugal (Teixeira, Silva, & Sa, 2021), New York, USA (Teixeira & Lopes, 2020), Columbus, USA (Kwon & Akar, 2023), and other cities. The findings should benefit the general transportation research communities. Bergantino, Intini, and Tangari (2021) argues that bike sharing can play a pivotal role in promoting healthy lifestyles and contributing to the goal of zero emissions currently being pursued, which goes beyond just transportation.

3.2. Clustering analysis on thematic noun phrases

Thematic noun-phrases, including keywords, can be extracted from the titles, keyword lists, and the abstracts of a reference database and hint at hot research topics. Similar to the co-citation network, a network of noun-phrases co-occurrence was built with 213 nodes and 512 links. However, the network obscures the underlying thematic similarities of keywords, so it is difficult to obtain useful information about distinguishable research topics from the network. Therefore, cluster analysis is conventionally applied to the co-occurrence network to identify significant topics that are organized in a community-like structure. CiteSpace provides an option for users to generate top clusters and name the clusters via an auto-tagging function that differentiates the clusters using tags from all the noun phrases extracted. The Log Likelihood Ration (LLR) was chosen to classify the phrases into groups to ensure that a cluster contains members with a high intra-class similarity and two different clusters have a low inter-class similarity. Fig. 4(b) displays the resulting clustering map and the LLR-based

Table 2
The top ten papers regarding bike-sharing patterns during COVID-19 pandemic according to citation frequencies.

Authors	Title	Network cited frequency	Overall cited frequency[a]
Teixeira and Lopes (2020)	The link between bike sharing and subway use during the COVID-19 pandemic: The case study of New York Citi Bike	47	441
Nikiforiadis et al. (2020)	Assessing the Impact of COVID-19 on Bike-Sharing Usage: The Case of Thessaloniki, Greece	36	146
Hu et al. (2021)	Examining spatiotemporal changing patterns of bike-sharing usage during the COVID-19 pandemic	35	139
Bucsky (2020)	**Modal share changes due to COVID-19: The case of Budapest**	33	535
Padmanabhan et al. (2021)	**COVID-19 effects on shared-biking in New York, Boston, and Chicago**	29	86
Wang and Noland (2021)	Bikeshare and subway ridership changes during the COVID-19 pandemic in New York City	28	141
Shamshiripour, Rahimi, Shabanpour, and Mohammadian (2020)	How is COVID-19 reshaping activity-travel behavior? Evidence from a comprehensive survey in Chicago	23	533
Bergantino et al. (2021)	Influencing factors for potential bike-sharing users: an empirical analysis during the COVID-19 pandemic	22	96
Shang et al. (2021)	Impacts of COVID-19 pandemic on user behaviors and environmental benefits of bike sharing: A big-data analysis	19	170
Jobe and Griffin (2021)	Bike share responses to COVID-19	18	70

Note: The papers with bold titles are also the top papers according to betweenness centrality (Table 3).
[a] The number of citations is obtained from Google Scholar as of Dec. 10, 2023.

Table 3
The top ten papers regarding bike-sharing patterns during COVID-19 pandemic according to betweenness centrality.

Authors	Title	Betweenness centrality
Jenelius and Cebecauer (2020)	Impacts of COVID-19 on public transport ridership in Sweden: Analysis of ticket validations, sales and passenger counts	0.24
Bucsky (2020)	**Modal share changes due to COVID-19: The case of Budapest**	0.17
Aloi et al. (2020)	Effects of the COVID-19 Lockdown on Urban Mobility: Empirical Evidence from the City of Santander (Spain)	0.17
Bergantino et al. (2021)	**Influencing factors for potential bike-sharing users: an empirical analysis during the COVID-19 pandemic**	0.15
Teixeira, Silva, and Moura e Sa (2022)	The role of bike sharing during the coronavirus pandemic: An analysis of the mobility patterns and perceptions of Lisbon's GIRA users	0.10
Barbarossa (2020)	The Post Pandemic City: Challenges and Opportunities for a Non-Motorized Urban Environment. An Overview of Italian Cases	0.10
Padmanabhan et al. (2021)	**COVID-19 effects on shared-biking in New York, Boston, and Chicago**	0.09
Kim (2021)	Impact of COVID-19 on usage patterns of a bike-sharing system: Case study of Seoul	0.09
El-Assi et al. (2017)	Effects of built environment and weather on bike sharing demand: a station level analysis of commercial bike sharing in Toronto	0.09
Chang, Lee, Yang, and Liou (2021)	Does COVID-19 affect metro use in Taipei?	0.09

Note: The papers with titles in bold are also top papers according to cited frequencies (Table 2).
Note: If two or more articles have the same betweenness centrality, they are sorted according to cited frequency by descending order.

rankings. More than 20 clusters were found, but the map only shows the top ten. The number #0 indicates that the cluster has the largest number of members. The clustering map has two evaluation indicators about goodness of fit. Modularity Q = 0.7008 shows that the clusters are significantly different from each other, and the mean silhouette of 0.8486 shows that the members within a cluster are similar and homogeneous. Top three clusters are bike-share, infection risk, and mode substitution. Cluster #0 (bike-share) ranks first, which is intuitive. Most of the studies surveyed contained this word in titles or keyword lists. The second largest cluster #1 is related to epidemiological aspects. During the initial outbreaks, people were concerned about crowded public transport vehicles that can facilitate virus transmission (Sträuli et al., 2022). Therefore, bike-sharing become an alternative commuting mode. This is also reflected by the alternative labels (i.e., cluster members) within cluster #1: emerging mobility services and general trip planning functions. These two labels have a higher frequency than other labels in the same cluster. In cluster # 2 (mode substitution), high-frequency alternative labels include shared mobility, mode choice, travel behavior, modal complementation, and COVID-19 lockdown. The substitutive potential of bike-sharing is in line with the previous discussions about the co-citation network (Section 3.1).

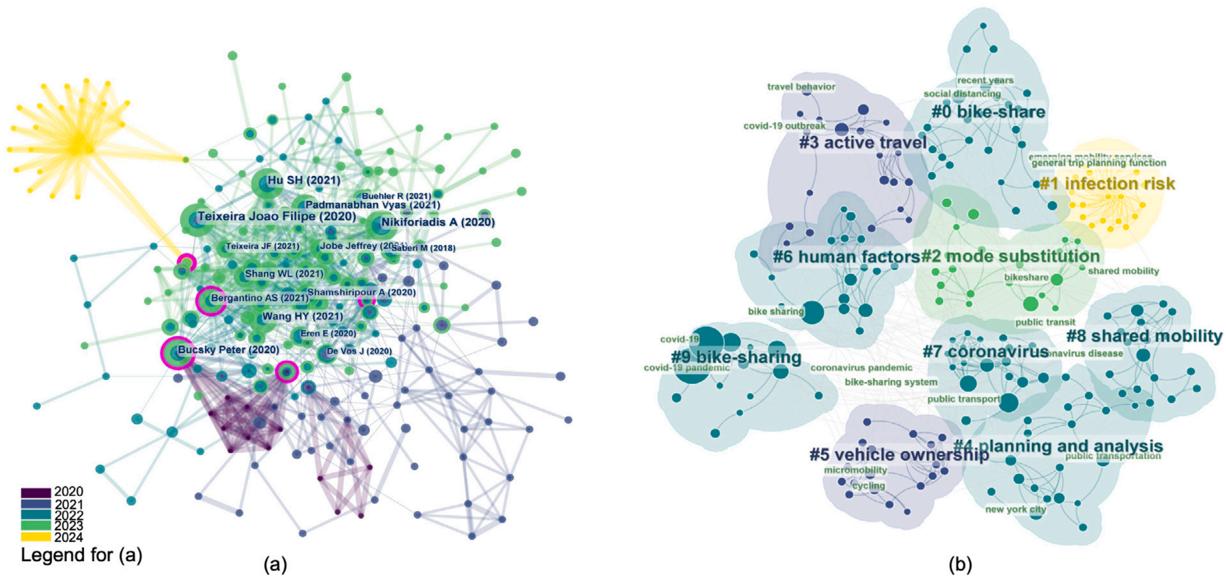

Fig. 4. A bibliometric analysis about bike-sharing usage under the impact of COVID-19. (a) Co-citation network. (b) Noun phrase co-occurrence network organized in clusters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. COVID-19 impacts on bike sharing ridership and user behaviors

Section 3 provides a high-level overview of the leading research topics on bike sharing in the last four years. This section provides an extensive review of studies exploring bike-sharing ridership and travel behaviors during the pandemic. Table 4 presents unique findings on case studies from various cities in Asia, Europe, and North America.

Bike-sharing ridership changes. It is not new to learn that ridership may increase or decrease in different cities, but our in-depth review reveals more subtleties about the underlying patterns. Specifically, we summarized six patterns of ridership change in the literature: dropped and recovered (DR); increased incrementally (IN); dropped, recovered, and rebounded (DRR); dropped incrementally (DI); increased initially and dropped afterwards (ID); and increased, decreased, and rebounded (IDR). DR is the most frequently observed pattern, appearing in 28% of the cities examined (Fig. 5), including Montgomery (Almannaa, Woodson, Ashqar, & Elhenawy, 2022) and Pittsburgh (Qin & Karimi, 2023) in the USA, Basel and Zürich in Switzerland Buchel, Marra, and Corman (2022), Beijing (Chai, Guo, Xiao, & Jiang, 2021) and Wuhan (Li & Xu, 2022) in China, and Valencia in Spain (Seifert et al., 2023). The usage of shared bikes decreased significantly during the lockdown (around between February and March 2020); however, it gradually returned to its usual rate afterward. IN is another interesting pattern, indicating that the pandemic may indirectly increase the adoption of bike-sharing services. The trend may continue after the first waves of infected cases. Examined cities are Rhodes, Chania, and Igoumenitsa in Greece (Bouhouras, Basbas, Ftergioti, Paschalidis, & Siakantaris, 2022), Singapore (Song, Zhang, Qin, & Ramli, 2022), Seoul in Korea (Jiao, Lee, & Choi, 2022; Jung & Kim, 2023; Kim & Cho, 2022; Park, Namkung, & Ko, 2023), and Columbus in the USA (Kwon & Akar, 2023). DRR reflects a unique pattern that specifically highlights the resilient nature of bike-sharing system. This pattern was seen in two of the most influential metropolises: London in the UK (Gao, Chen, & Haworth, 2023; Heydari, Konstantinoudis, & Behsoodi, 2021) and New York in the USA (Bi, Ye, Zhang, & Zhu, 2022; Pase, Chiariotti, Zanella, & Zorzi, 2020; Wang & Noland, 2021). Barcelona in Spain (Bustamante, Federo, & Fernandez-i Marin, 2022) and Lisbon in Portugal (Teixeira et al., 2021) echo the DRR pattern as well. Their bike-sharing systems exhibit a strong rebounding momentum, with cycling usage in 2022 potentially surpassing the pre-pandemic level (Shi, Zhao, He, & Xu, 2023). Around 10% cities saw their bike-sharing ridership in a constantly declining trend exhibiting the DI pattern, including Nanjing in China (Hua, Chen, Cheng, & Chen, 2021), Madrid in Spain (Arias-Molinares, Garcia-Palomares, & Gutierrez, 2023), and Lane County in the USA (Ngo & Martin, 2023). Similarly, approximately the same share of cities observed a pattern of ID: the ridership increased shortly after the lockdown but dropped gradually as transport restriction measures were lifted. The cases in point are Budapest in Hungary (Berezvai, 2022; Jaber, Csonka, & Juhasz, 2022), Austin in the USA (Basak, Al Balawi, Fatemi, & Tafti, 2023), and Daejeon in Korea (Sim, 2023). Lastly, IDR was observed only in Chicago, USA (Hu et al., 2021). The bike-sharing usage initially grew in March 2020. It declined in April and May and began to rebound in June 2020 due to people returning to work and schools.

Changes in travel behaviors of bike-sharing users. The changes are threefold. First, the duration and distance of cycling trips appear to be higher than those before the pandemic (Almannaa et al., 2022). For example, Davidson et al. (2022) states that the pandemic had a positive impact on the length of trips, leading to an increase of around 7.46 min. Second, the number of commuter trips declined, which was compensated for by an increasing number of leisure trips. This is somehow related to the first point. The pandemic has had a significant effect on the travel habits of commuters, including a decrease in commuters and an increase in trips for leisure and entertainment activities (Bi et al., 2022). This phenomenon is echoed by Hu et al. (2021) and Kim (2021), who reported that commuter trips decreased significantly during the first quarter of 2020, while leisure trips expanded. Lastly, biking trips seem to substitute bus or subway rides to meet essential needs when available options are extremely limited. For example, Sim (2023) reported the preference of commuters for biking over public transport, even for longer trips. Similarly, there has been reported to be a possible modal shift from bus in Lisbon, Portugal (Teixeira et al., 2022) and from subway in New York, USA (Teixeira & Lopes, 2020).

While the scientometric review provides valuable insights into broad patterns and trends in bike-sharing research during the COVID-19 pandemic, it also reveals gaps in our understanding of specific behavioral changes at a local level. To address this, we conducted a detailed case study of New York City's Citi Bike program. This case

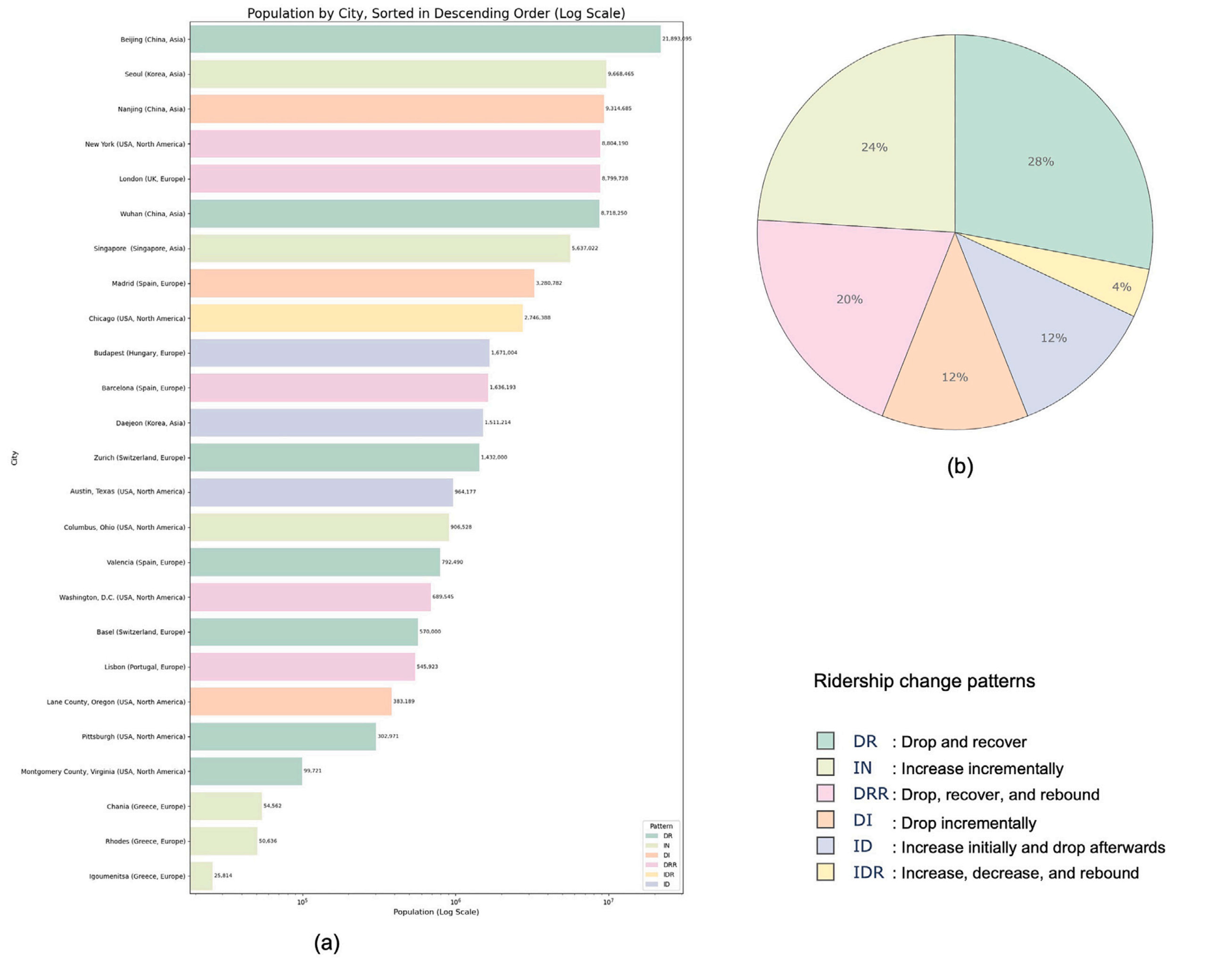

Fig. 5. The ridership change patterns of examined cities in the literature during the pandemic. (a) Total population of each examined city in a descending order. (b) The breakdown of each pattern.

study allows us to examine how the patterns identified in the literature review - particularly the decrease-recover-rebound cycle and changes in trip purposes - manifest in a major urban center. Additionally, it enables us to explore nuances and potentially identify new patterns not yet widely documented in the literature.

To facilitate statistical inference, this study developed a procedure to infer the purposes of trips in different pandemic periods, as shown in Section 2.3. New York, USA was selected to test the research hypothesis due to openly available bike sharing datasets and other geospatial information.

4. Case study results

4.1. The temporal dynamics of bike-sharing trips

The general trend of bike-sharing ridership is consistent with the pattern described in Section 3.3: a decrease-recover-rebound cycle from March 2020 to the end of March 2022 (Fig. 6). The first case of COVID-19 was confirmed in New York state on 1 March 2020. Around two weeks later, a patient in New York City died of COVID-19. As a result, public schools closed and a stay-at-home order was issued in the week of March 16, 2020. The state of emergency extended until the end of May, when transport contingency measures began to be lifted. The lockdown significantly affected bike sharing usage, leading to a reduction in ridership as high as 70%. However, the bike-sharing system is surprisingly resilient. The daily number of trips rebounded to 80,000 on average in August 2020, when the city progressively opened up permits for social gatherings and restored public transport. Moreover, the bike-sharing ridership experienced a steadfast recovery and substantial growth even in 2022, when the number of daily new cases reached an all-time high in the city. The general trend of bike-sharing ridership in New York City follows the drop-recover-rebound (DRR) pattern, which aligns with findings from Bi et al. (2022) and Wang and Noland (2021) for the same city, as well as observations in other major cities like London (Gao et al., 2023; Heydari et al., 2021).

4.2. Clustering outcomes of major trip purposes

4.2.1. Major trip purposes across four pandemic periods

Fig. 7 shows the results of the clustering algorithm and the procedure developed to infer the purposes of the trip. The horizontal axis denotes the types of land use at the origin and destination of a trip. For example, R-C means that a trip starts in a residential parcel and ends in a commercial parcel. An automatic script was developed to identify a chain of the same cluster label by the types of land use at the origins and destinations of the trips. The key was to compute the pairwise Euclidean distances between any given pair of cluster labels in two consecutive periods. Each label refers to a vector of the number of trips by a land use pair. For example, label No. 2 in period 1 is a vector of dimension 35 (the total number of land use pairs), with the

Table 4
Observations about bike-sharing ridership and travel behaviors under the impact of COVID-19 (ordered by the author names alphabetically).

Authors	Study areas	Ridership change patterns	User behaviors
Almannaa et al. (2022)	Montgomery County, Virginia, USA	DR[a]: The system underwent a marginal drop in 2019 to 2020, but an upward trend in 2021.	Trip distance and duration increased.
Arias-Molinares et al. (2023)	Madrid, Spain	DI[a]: The usage of micromobility services in Madrid decreased by approximately 10% during the pandemic, with BiciMAD (a major operator) making up 78.1% of all trips and experiencing a higher rate of utilization after the onset of COVID-19.	The activities around residential and commercial areas increased while the importance of workplace locations, educational facilities, and transport facilities declined due to teleworking and online learning.
Basak et al. (2023)	Austin, Boston, Chicago, and a few cities in the USA	ID[a]: They noticed an average rise of 22% in the amount of daily bike-sharing journeys after the initial Covid-19 case and a decrease of 30% in the amount of daily bike-sharing trips after the first executive order was issued.	
Berezvai (2022)	Budapest, Hungary	ID[a]: The usage increased following governmental stringency measures but declined after the measures were lifted and failed to reach the pre-pandemic level.	
Bi et al. (2022)	New York, USA	DRR[a]: The demand experienced a slight fluctuation prior to the outbreak and then dropped dramatically in March. However, it began to recover in April and dramatically increased in May, with performance returning to the same level as in 2019.	The pandemic has had a significant effect on people's travel habits, including a decrease in commuting and an increase in trips for leisure and entertainment activities.
Bouhouras et al. (2022)	Rhodes, Chania, Igoumenitsa, Greece	IN[a]: The lockdown period had a beneficial outcome on the utilization of bike-sharing systems, with a rise in usage during and after the lockdown.	
Buchel et al. (2022)	Basel, Zürich, Switzerland	DR[a]: The use of bicycles decreased significantly during the lockdown; however, it quickly returned to its usual rate afterward.	There was a shift of morning traffic towards early afternoon.
Bustamante et al. (2022)	Barcelona, Spain	DRR[a]: Increase in bicycle usage after the lockdown	
Chai et al. (2021)	Beijing, China	DR[a]: The pandemic caused a decrease of 64.8% in the use of bicycles. However, there was a rise of 15.9% in the utilization of shared bikes, suggesting a partial return to work-related and residential activities.	The mobility near subway stations, tech firms, and shopping centers was more impacted than other types of land use.
Chen, Sun, Deveci, and Coffman (2022)	Washington, D.C., USA	DRR[a]: The number of bike-sharing rides declined substantially following the lockdown in March 2020. By the winter of 2021, the number of users had returned to normal.	
Davidson et al. (2022)	Philadelphia, USA		The pandemic had a positive impact on the length of trips, leading to an increase of around 7.46 min.
Gao et al. (2023)	London, UK	DRR[a]: The researchers noticed a decrease in trips during the period of lockdown, which was then followed by a resurgence to levels higher than those of 2019 between May and September.	In the morning peak, commuting trips were substituted by more leisurely activities, particularly in London's parks. However, commuting activities resumed, but with a change in timing, with a decrease in morning peak activity and an increase in other time periods.
Hu et al. (2021)	Chicago, USA	IDR[a]: Ridership initially increased in March 2020. The volume decreased in April and May; the number began to rebound in June 2020 due to returning to workplaces and schools.	Commuting trips decreased significantly during the pandemic, while leisure trips increased.
Hua et al. (2021)	Nanjing, China	DI[a]: The number of trips reduced by 72%.	They observed a significant decrease in commuting travel and a rise in shopping, scenery, health, religion, and residence.
Jiao et al. (2022)	Seoul, Korea	IN[a]: The study observed an increase in bike-sharing usage during the COVID-19 pandemic.	
Kim (2021)	Seoul, Korea		The demand for bikes for leisure purposes expanded during outbreaks.
Kwon and Akar (2023)	Columbus, Ohio, USA	IN[a]: During the pandemic, bike-sharing trips increased, while bus ridership reduced.	Lockdowns led to a phenomenal increase in substitutive trips, particularly on weekdays.
Li and Xu (2022)	Wuhan, China	DR[a]: There was a substantial reduction in trips in February 2020, with a subsequent increase in October 2020.	Less activities occurred in urban centers compared with those in the suburbs.

(*continued on next page*)

Table 4 (*continued*).

Ngo and Martin (2023)	Lane County, Oregon, USA	DI[a]: The ridership experienced a decline of 68% in the three 90-day periods after the start of the lockdown.	Bike-sharing ridership is positively associated with neighborhoods mainly consisting of young, elderly people, while negatively related to the communities of high-income households and workers in the food service and agriculture sectors.
Qin and Karimi (2023)	Pittsburgh, USA	DR[a]: In April 2020, there was a considerable decrease in the number of trips taken, which was followed by a recovery in the months that followed.	
Seifert et al. (2023)	Valencia, Spain	DR[a]: There was a 40% reduction in trip volume after the outbreak, consistent recovery observed duwithring the rest of 2020.	
Sim (2023)	Daejeon, Korea	ID[a]: The number of rentals in 2019 is 553,249, while that figure increased to 604,446 in 2020 but decreased to 522,716 in 2021.	A transition occurred from commuting to other daily trips and a preference for bicycles over public transportation was observed, even for longer trips.
Song et al. (2022)	Singapore	IN[a]: The bike-sharing usage increased during the COVID-19 pandemic, with a two-fold increase during the lockdown and a four-fold increase in July 2020 compared to pre-pandemic levels.	A multipolar spatial structure developed.
Teixeira et al. (2021)	Lisbon, Portugal	DRR[a]: Ridership rebounded to pre-pandemic levels.	There was a potential modal shift from bus to bike rides.

[a] Note: We observed that the ridership in different cities follows general patterns, as summarized below. IN: Increase incrementally; DI: Drop incrementally; ID: Increase initially and drop afterwards; DR: Drop and recover; DRR: Drop, recover, and rebound; IDR: Increase, decrease, and rebound.

dominant entry being the eighth entry, that is, the number of C–C trips (Fig. 7(a)). This vector has the smallest distance to the one with the cluster label No. 0 in period 1 (Fig. 7(b)) which was the closest to the cluster label No. 3 in period 3 (Fig. 7(c)). Consequently, a chain of C–C trips was detected. The same procedure was also applied to other labels.

Although more than ten clusters are identified, the top ones are highlighted by dashed rectangles in the figure. Before the pandemic, work-related trips (group numbers #2 and #3) played an important role, as indicated by the green dashed rectangle in Fig. 7(a). Cluster #2 can be considered as work trips, because it is dominated by a C–C label. Cluster #3 can be inferred as commuter trips because there appears to be a symmetric distribution between the C-R and R-C labels. More than 1,000,000 combined trips before the pandemic are related to work or commuting. On the contrary, residential trips (cluster #4 highlighted by the red dashed rectangle in Fig. 7(a)) appear to be a smaller cluster. Compared to work, commuting, and residential trips, other trip purposes, such as leisure or entertainment (P-P or R-P labels in the figure), are insignificant during this period.

During period 2 (from 2020/03/17 to 2020/05/01), residential trips began to accumulate, as suggested by the red rectangle in Fig. 7(b). Furthermore, the share of residential trips continued to increase substantially during periods 3 and 4. Some implications can be drawn from the cluster matrices. First, bike-sharing is an important mode of transport at different stages of the pandemic. Second, the preference for bike-sharing is maintained throughout the COVID-19 outbreak. Lastly, work and residential trips are the main purposes of trips during the pandemic, outweighing other purposes such as leisure and shopping. The dominance of major trip purposes such as work trips continued to reinforce in the coming years (2021 and 2022) as well (Figs. A.1 and A.2), despite the record-high number of daily COVID-19 cases in early 2022 (Fig. 6).

4.2.2. Time of the day patterns of residential trips

Previous studies have demonstrated that COVID-19 resulted in an increase in both the duration and distance of bike-sharing trips (Almannaa et al., 2022; Heydari et al., 2021). Cycling traffic is also reported to tend to shift towards the afternoon (Buchel et al., 2022). These findings are consistent with what this study discovers (Fig. 8). Both residential and commercial trips show a similar time-of-the-day structure, but only residential trips are discussed to avoid redundancy. Residential-to-residential trips shifted towards afternoon and evening peaks, and on weekdays the traffic largely concentrated around evening peaks (from 05:00 pm to 08:00 pm). Working from home and telecommuting can be the main causes of the shift. Furthermore, this temporal pattern seems to consolidate even if the city declared the end of the emergency stage and opened up gradually. The average travel distance increased by approximately 800 m from period 1 to 4. In particular, in period 3, there existed longer trips on weekends than on weekdays, which is the most obvious compared to the situations in the other three periods. Longer bike-sharing trips may be driven by different factors. One promising reason is that people chose to replace bus or train trips with bike sharing, which is considered less vulnerable to infectious diseases with a high transmission rate in an enclosed environment (Sträuli et al., 2022). Another cause may be ascribed to the increasing demand for physical activities for leisure purposes, such as cycling in the city or in parks. These activities have a longer duration or travel distance. However, the importance of leisure trips is not reflected in the clustering matrices (Fig. 7).

The situations in 2021 and 2022 indicate certain degrees of the behavioral change of cyclists, compared to what is observed in 2020 (Fig. 9). Morning and afternoon peaks appeared again in 2022. Additionally, bike-sharing users on residential trips generally traveled longer distances in 2021 and 2022 than they did in 2020 (Fig. B.1).

4.2.3. Spatial patterns of residential and work trips

Fig. 10 shows the spatial clusters of residential and working trips, which remains consistent from 2020 to 2022. These areas have seen increased traffic during the four pandemic periods. These areas are mainly within lower and central Manhattan, western Queens, and northern Brooklyn, where bike stations are located. Apartments, luxury residences, residential&commercial complexes, and college dormitories are the main types of residential land use with a high volume of bike traffic (Fig. 10(a)). This implies that bike-sharing are generally accepted as a viable option by households of different income levels when other alternatives become limited. Furthermore, the clusters of work trips are well depicted and enclosed within the Manhattan CBD district where most financial and commercial activities occur in the city (Fig. 10(b)). Specifically, increased bicycle traffic is observed at stations near financial towers and headquarters such as the Empire State Building, the New York Stock Exchange, and Wall Street. These trips directly connect types of commercial land use, indicating that bike sharing is widely adopted by people working from the office to reach

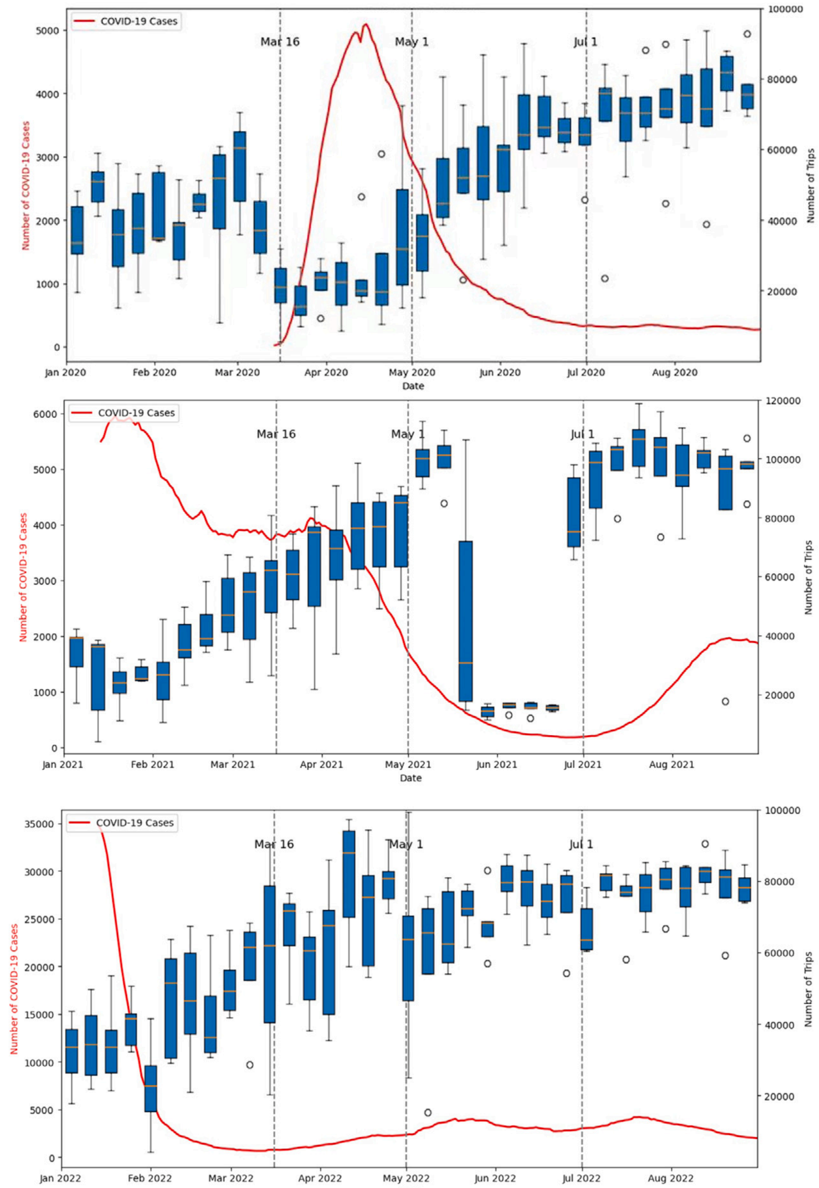

Fig. 6. Daily number of bike-sharing trips and newly confirmed COVID-19 cases in 2020 (upper), 2021 (middle), and 2022 (bottom) in the City of New York, USA. The red lines represent the COVID-19 trends. The box plots are the monthly distributions of daily trip amount. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

different work locations. The concentration of increased bike traffic in lower and central Manhattan, western Queens, and northern Brooklyn is similar to patterns observed by Hu et al. (2021) in Chicago, where certain areas saw more significant changes in bike-sharing usage than others.

4.3. Temporally significant changes in residential and work trips

Table 5 shows that there exist statistically significant changes in the amount of work and residential trips at the community level before and after the first wave of COVID-19 hit New York City in 2020. Only two of the 25 communities see no change in the number of work or residential trips. For those communities with significant changes in residential trips, about 63% sees a growth from period 1 to period 2. For example, the average percentage of residential trips in community 107 is 18.62% in period 2, up from 14.25% in period 1. On the other hand, ten of the 18 communities (approximately 55%) witness a rise in work trips. Also take community 107 for example. The average percentage of work trips in period 2 is 28.03%, approximately 8% lower than the level in period 1. The relative changes between residential and work trips in a community suggest that there may exist a substitutive effect among them. Generally speaking, although the number of communities with an increased percentage of work trips is on the rise, it is not comparable to the case of residential trips.

Fig. 11 shows the direction of changes in residential and work trips in a spatial context during the early stages of the pandemic in New York City. The percentage of residential trips increased significantly in almost all communities in Manhattan and one large community in North Queens. Interestingly, a reverse trend is observed for work trips: the share of work trips declined significantly in the city core (Manhattan), whereas peripheral areas in Brooklyn and Queens see a growth of the share. The shift in the percentages of trips within

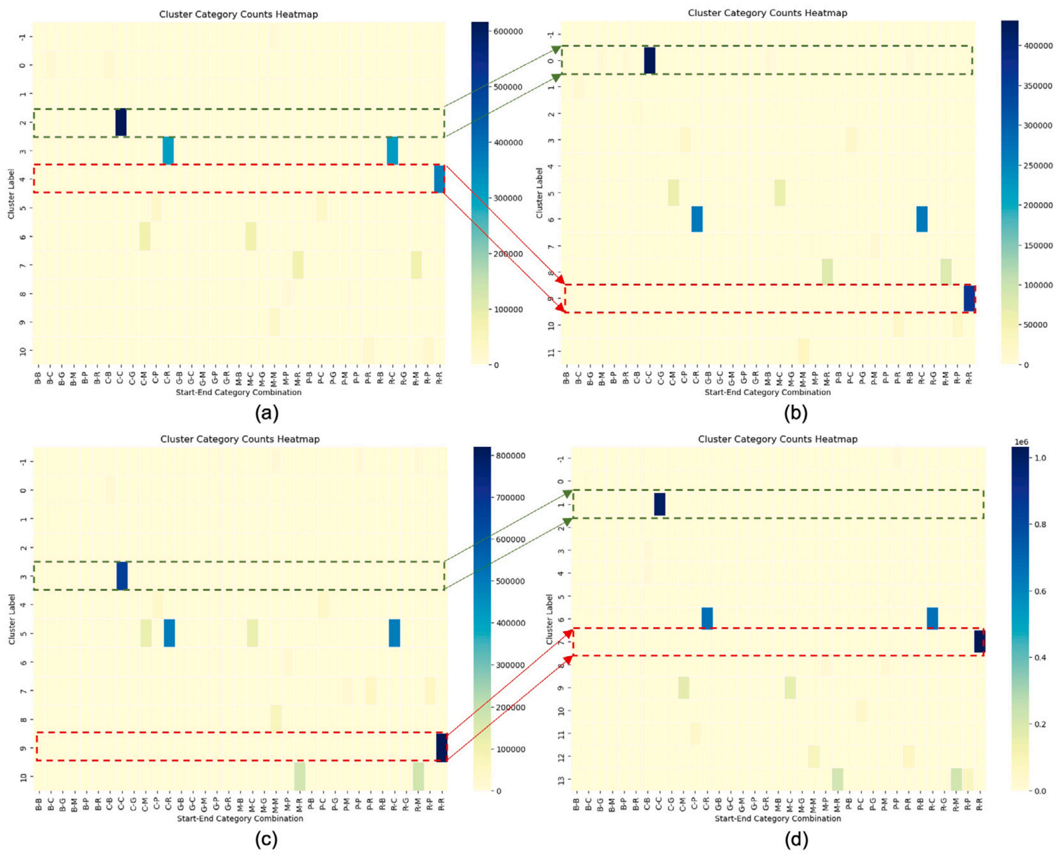

Fig. 7. The breakdown of the number of trips according to the land use types at origins and destinations for each cluster label during the four periods in 2020. Dashed boxes of the same color denote the main purpose of the trip for the four periods. C - commercial. R - residential. M - manufacturing. P - parks. G - playground. B - battery park city. For example, C–C denotes those trips with the type of land use of both their origins and destinations as commercial. (a) to (d) - from period 1 to 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

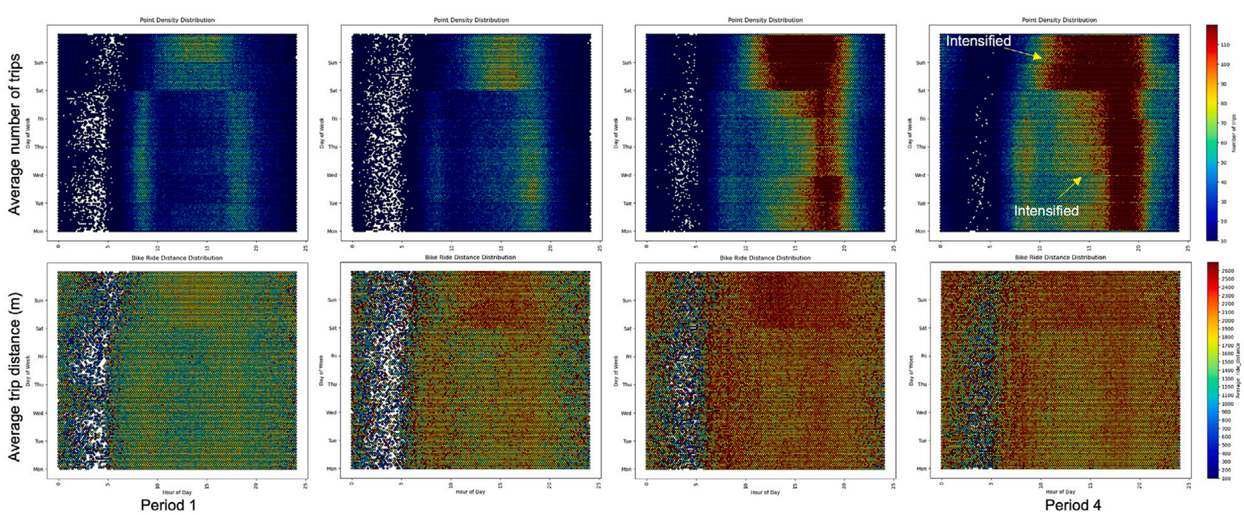

Fig. 8. The time-of-the-day patterns of residential-to-residential trips across four periods in 2020. Upper - number of trips. Lower - trip distance (m). Left to right - from periods 1 to 4.

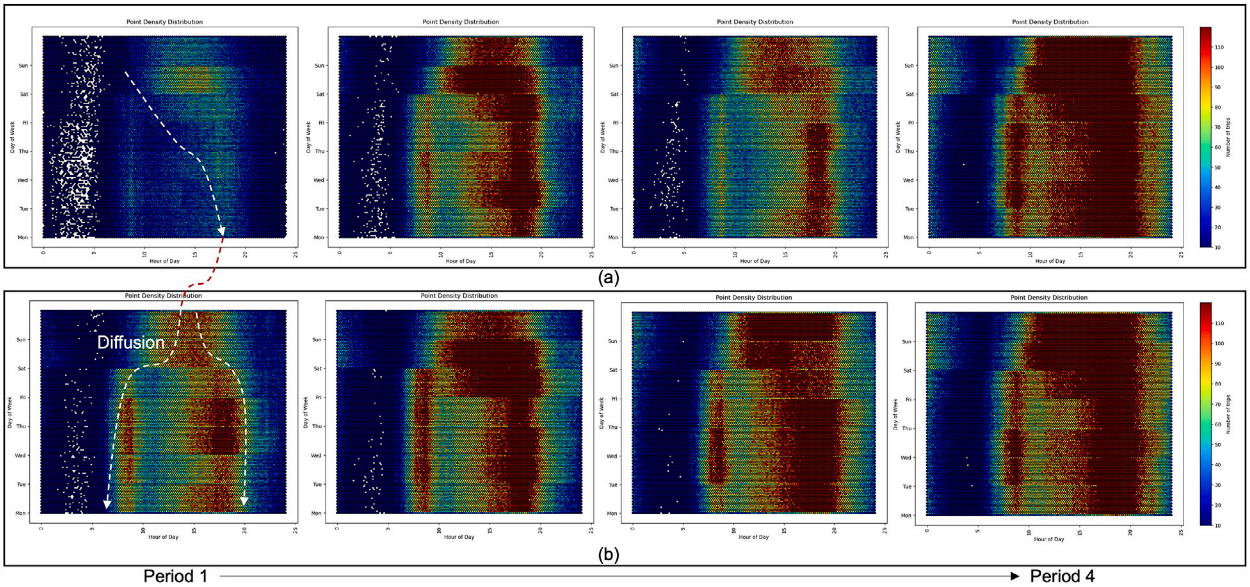

Fig. 9. The time-of-the-day patterns of the average number of residential-to-residential trips over four periods in (a) 2021 and (b) 2022. Left to right - from periods 1 to 4.

Table 5
The results of the Mann–Whitney U tests that compare the proportion of the number of working and residential trips for individual communities before and after the onset of the COVID-19 pandemic in 2020.

Community identifier	Residential to residential (%)			Commercial to commercial (%)		
	Period 1	Period 2	Direction	Period 1	Period 2	Direction
101	0.00	0.00	–	51.42	52.91	–
102	8.92	9.41	U**	30.05	29.48	–
103	23.44	27.51	U**	13.46	11.91	D**
104	2.55	3.73	U**	46.22	41.83	D**
105	2.03	2.84	U**	59.35	52.37	D**
106	9.50	13.63	U**	41.37	34.31	D**
107	14.25	18.62	U**	35.50	28.03	D**
108	17.91	20.72	U**	29.40	25.14	D**
109	58.29	47.42	D**	0.00	0.28	U**
110	46.54	47.83	U**	6.47	5.77	D**
111	54.05	55.34	U**	2.84	1.90	D**
164	51.42	50.46	–	0.00	0.07	U**
301	37.41	36.58	D**	1.20	1.21	–
302	27.16	26.90	–	9.05	10.16	U**
303	55.07	52.76	D**	0.67	0.88	U**
304	51.08	51.23	–	0.92	1.04	–
306	40.83	36.35	D**	3.25	3.21	–
307	0.00	0.00	–	0.00	0.10	–
308	64.58	64.16	–	0.00	0.07	U**
309	45.44	42.98	–	3.22	5.12	U**
316	28.77	19.86	D**	9.95	12.94	U**
355	79.10	73.49	D**	0.00	0.03	U**
401	36.93	39.90	U**	2.63	2.59	–
402	23.52	22.55	–	0.31	0.56	U**
405	49.39	47.73	–	0.38	0.54	U**

U, D denotes up and down, respectively.
– No change or statistically insignificant change.
** Significant at the 95% confident level.

a community may suggest that work trips are partially substituted for residential trips in Manhattan, which is home to the majority of economic activities in New York. The potential substitution of work trips by residential trips in Manhattan aligns with findings from Kwon and Akar (2023) and Teixeira and Lopes (2020), who observed bike-sharing replacing some public transit trips in New York and Columbus, respectively.

The overall demand for bike sharing as a transport mode for residential trips declined in the first half of 2021 and 2022, as demonstrated by the comparison year by year (Fig. 12). Although residential trips account for the highest proportion in almost all communities, their decline is also statistically significant (Fig. C.1). On the other hand, the spatial patterns of commercial trips in 2021 and 2022 remain consistent compared to the conditions in 2020.

5. Discussions, conclusions and implications

5.1. Discussion

The scientometric analysis and the exploration of travel behaviors of bike-sharing users in New York City provide valuable insights into the development of a sustainable and resilient transportation system in the post-coronavirus era. The scientometric analysis highlights several highly debated research interests: emerging mobility services, mode

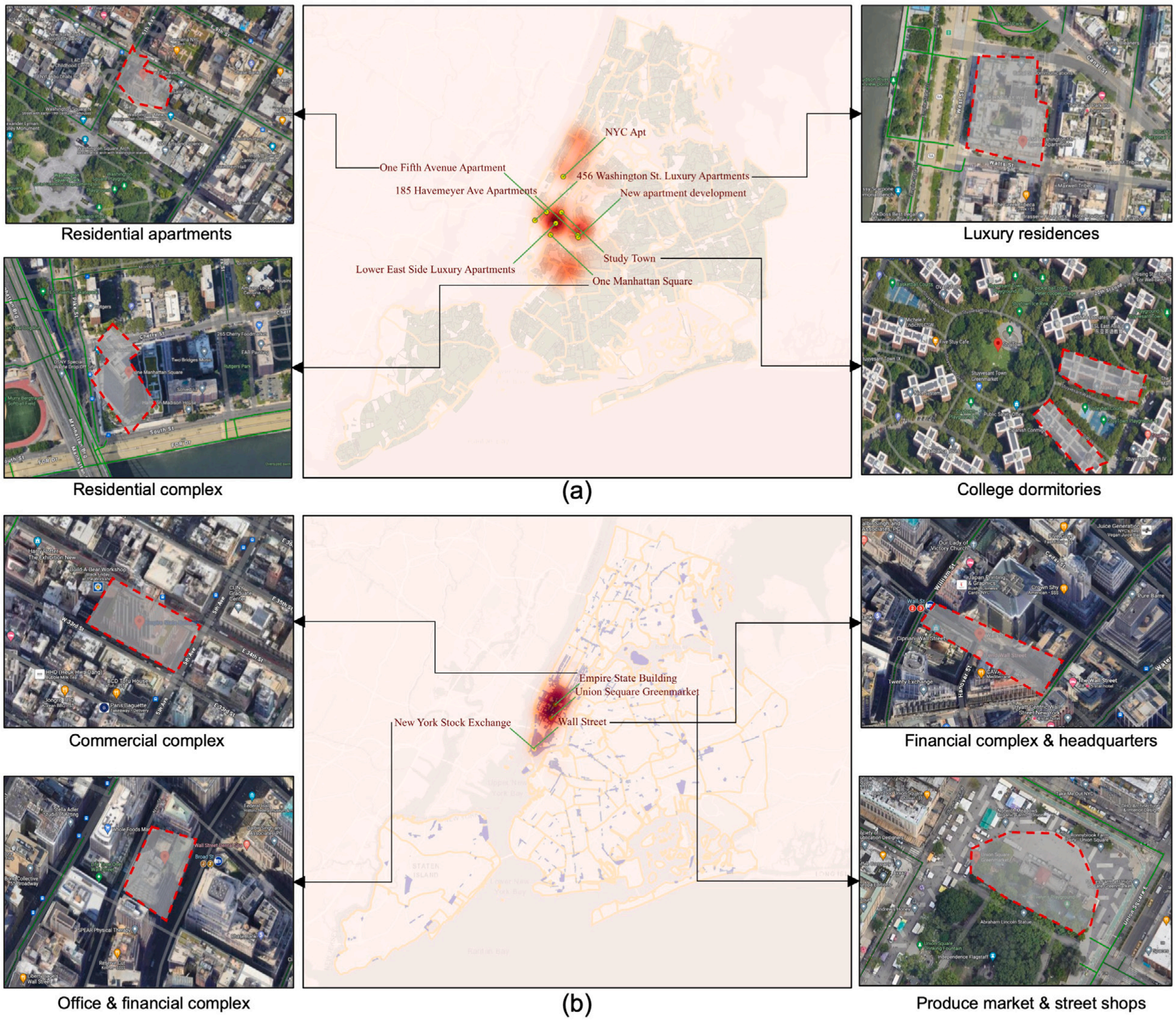

Fig. 10. Spatial heatmaps of the bike-sharing trips that sustain the initial cycles of the pandemic. (a) Residential to residential. (b) Commercial to commercial.

substitution, mode choice, and modal complementation. These phrases frequently appear in the examined publications, indicating continued demand for daily mobility needs and suggesting that shared biking systems are a timely and efficient addition (or "remedy") to a degraded public transportation system during the COVID-19 lockdown. These implications are echoed by the results of our case studies, which show a significant increase in the adoption rate of bike-sharing facilities for essential travel purposes within residential and commercial areas before and after the rapid onset of the COVID-19 pandemic in New York City. Interestingly, people switched to other modes when the threats from COVID-19 decreased in 2022. Although the devastating power of COVID-19 has faded over time, society still experiences waves of new virus variants that threaten vulnerable population groups and disturb urban economies. This implies that cities must be prepared for the long-term coexistence with an unstable infectious disease. As the backbone of physical and economic flows, the transportation system's development and maintenance should consider this uncertainty.

Many examined studies have demonstrated the resilient capacity of bike-sharing, with ridership rebounding even above pre-pandemic levels, characterized by a decrease-recover-rebound pattern. This pattern is also observed in the New York City case study. Therefore, bike-sharing, along with other emerging shared micro-mobility options such as e-scooters, should be factored into transportation infrastructure planning and travel demand prediction, which is currently absent. When situations worsen due to new COVID-19 waves, a resilient bike-sharing system can sustain different stages of the pandemic and ease the pressure of meeting mobility needs due to the possible shutdown of other essential transit modes.

The observations from this study offer insights for developing post-pandemic transportation policies. Modal shift from bus or subway to bike-sharing has been demonstrated by previous studies as well (Teixeira & Lopes, 2020). However, we also observe that commuters adopt shared bikes less often for certain trip purposes, such as residential trips, after society enters a new stage where coexistence with COVID-19 may become the new norm. While COVID-19 provides the context, the underlying factors driving the modal shift are more likely to be changed working hours and locations, health concerns, and campaigns promoting a greener transportation system. These driving forces should be studied in detail by planners and policymakers to cultivate genuine and sustainable shifts from vehicles to bikes and other greener modes. Additionally, bike-sharing brings other benefits, including a healthier lifestyle and fewer carbon emissions. The post-coronavirus era is both a long-lasting challenge and an opportunity to strengthen the role of bike-sharing in a sustainable transport system.

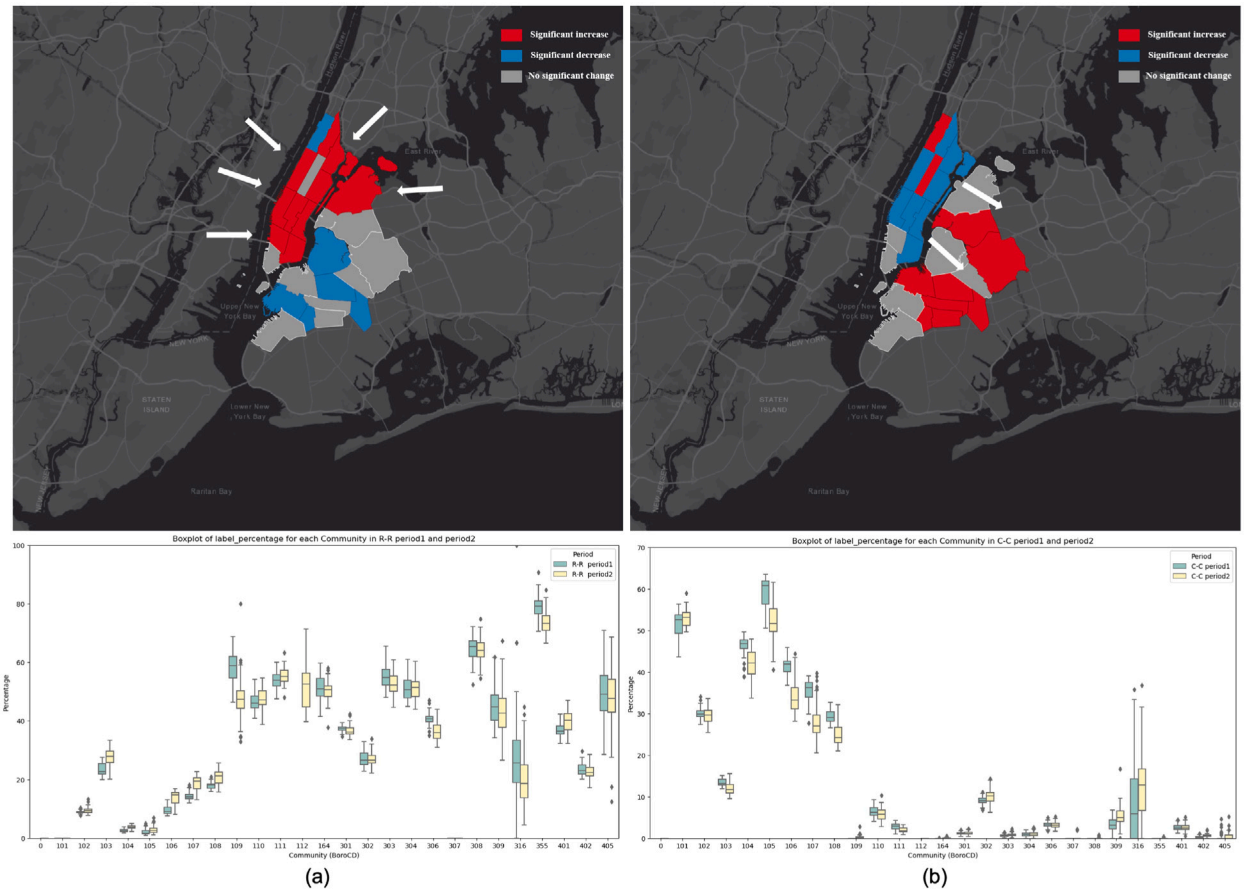

Fig. 11. The comparison of the percentage of bike-sharing trips in communities before and after the first COVID-19 case was confirmed in 2020. (a) Residential to residential. (b) Commercial to commercial.

5.2. Conclusions

COVID-19 is still an ongoing concern, but its impacts on emerging mobility modes such as bike-sharing are not yet well understood. This study reviewed the latest findings from the past four years through scientometric analysis and identified unanswered research questions explored in a case study using open bike-sharing datasets from the Citi Bike program in New York City, USA. The scientometric analysis focused on identifying important articles in relevant fields and trending research topics using a quantitative approach based on complex network theories. A clustering-based procedure was developed to identify major travel purposes in different pandemic periods, and statistical inferences were made about changes in trip purposes before and after COVID-19 evolved.

According to the scientometric analysis, Nikiforiadis et al. (2020), Teixeira and Lopes (2020) and Hu et al. (2021) are the top three articles receiving the most citations from the examined bike-sharing documents. Jenelius and Cebecauer (2020) is considered one of the most influential articles bridging active mobility, public transport, and other knowledge domains. An in-depth review of 24 case study articles reveals that the evolving changes in bike-sharing ridership through the pandemic can be categorized into six types. A drop-recover-rebound cycle is observed in bike-sharing systems in New York City and London, suggesting that the shared mode is resilient to the pandemic. People's travel behaviors evolved as well, with bike-sharing trips appearing longer in duration and distance, substituting buses or subways for longer trips.

The analysis of recent literature raises the question of whether changes in travel behavior are significant. This hypothesis was demonstrated by a case study in New York City, USA, identifying residential and work trips as the top trip purposes. Both types of trips sustained different stages of the pandemic, showing strong spatiotemporal robustness. The hypothesis testing on the percentage change of residential and work trips at the community level shows significant growth in both types of trips before and after the COVID-19 outbreak in New York, with residential trips experiencing a slightly higher increase in terms of the number of communities.

5.3. Implications

There are several limitations to this study. First, the case study only examined situations in New York City, so the derived conclusions may not be applicable to other cities. A global study is necessary to make the insights more generalizable. Spatiotemporal mobility patterns can change over time, and it is important to see if bike-sharing remains a resilient option as COVID-19 becomes endemic. The validity of some of our observations may not hold in the longer term. Secondly, the review focuses overwhelmingly on bike-sharing, which can be expanded to account for other transport modes to present more convincing and emerging findings from the literature. Third, insights from the literature review should be taken with a grain of salt, as only publications from the past four years were reviewed. Lastly, modal substitution between bike-sharing and other transport modes is still an open debate, warranting more rigorous inquiries in the future.

Decision-makers can learn from these observations to develop post-pandemic transportation policies. Modal shift from bus or subway to bike-sharing has been demonstrated by previous studies as well. However, we also observe that commuters adopt shared bikes less often for certain trip purposes, such as residential trips, after society enters a new stage where coexistence with COVID-19 may become the new norm.

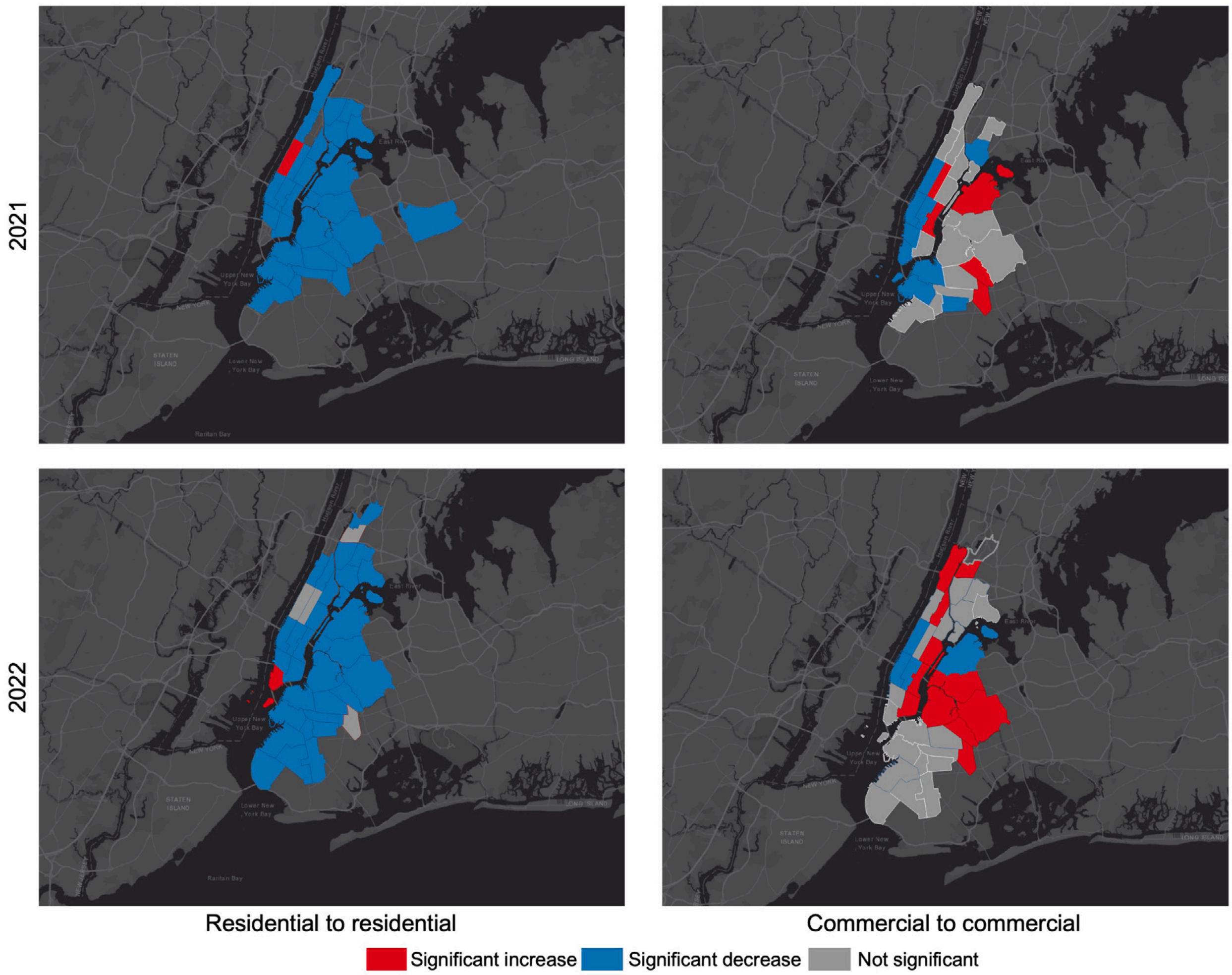

Fig. 12. The year-by-year comparison of the percentage of bike-sharing trips of different communities in period 1 (from January 20 to March 16) and period 2 (from March 17 to May 1). Significant level - 0.05; First column - residential-to-residential trips; Second column - commercial-to-commercial trips; First row - 2021; Second row - 2022.

The underlying factors driving the modal shift are more likely to be changed working hours and locations, health concerns, and campaigns promoting a greener transportation system. These driving forces should be studied in detail by planners and policymakers to cultivate genuine and sustainable shifts from vehicles to bikes and other greener modes. Additionally, bike-sharing brings other benefits, including a healthier lifestyle and fewer carbon emissions. The post-coronavirus era is both a long-lasting challenge and an opportunity to strengthen the role of bike-sharing in a sustainable transport system.

CRediT authorship contribution statement

Liye Zhang: Methodology, Funding acquisition, Conceptualization. **Zhongzheng Li:** Writing – original draft, Methodology, Formal analysis. **Jie Song:** Writing – original draft, Formal analysis, Conceptualization. **Rui Zhu:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Bike-sharing trip purposes based on land use types in 2021 and 2022

See Figs. A.1 and A.2.

Appendix B. Time-of-day patterns of residential-to-residential trips in 2021 and 2022

See Fig. B.1.

Appendix C. The comparison of bike-sharing trips in 2021 and 2022

See Fig. C.1.

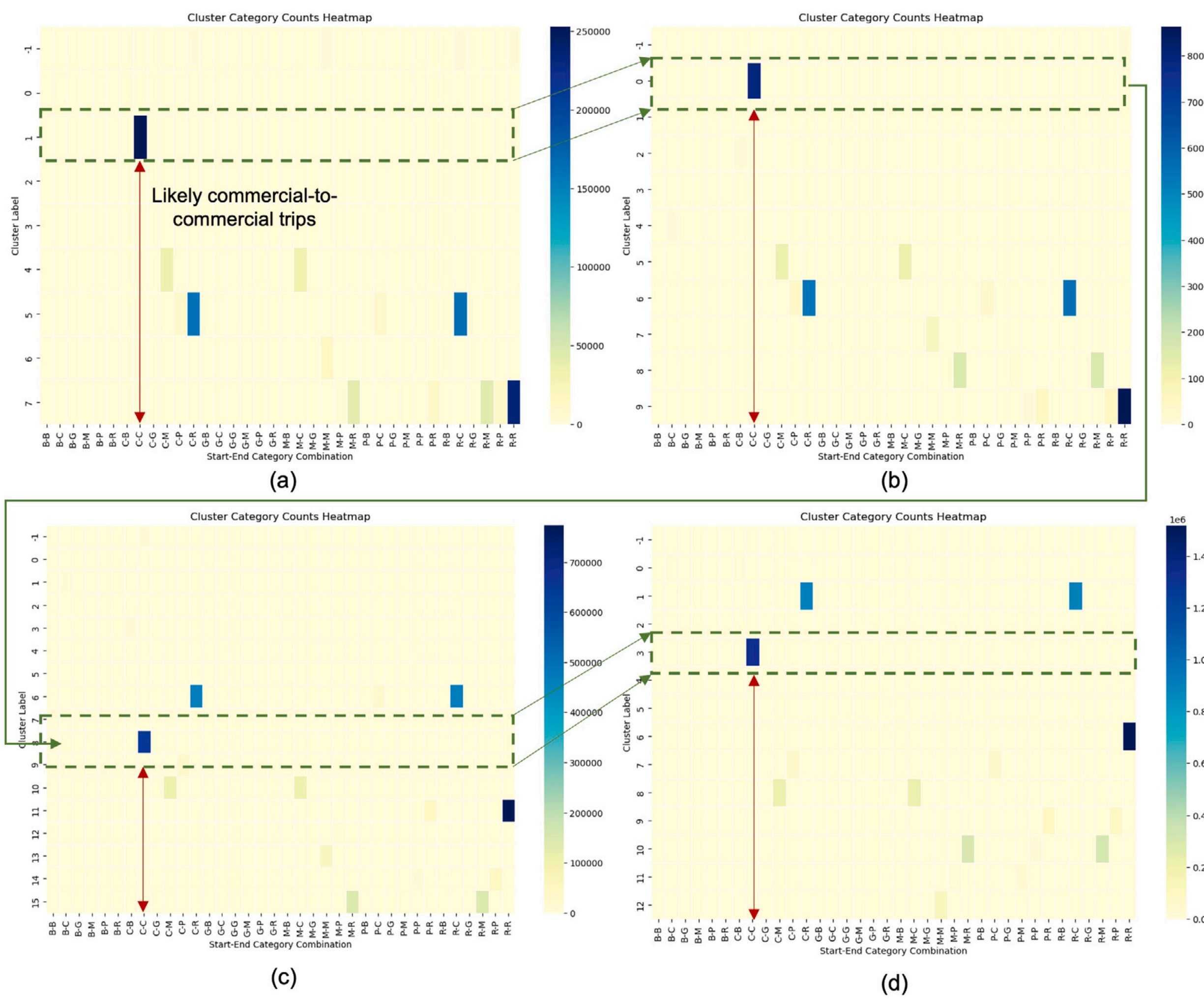

Fig. A.1. The breakdown of the number of trips according to the land use types at origins and destinations for each cluster label during the fixed four periods in 2021: (a) 2021/01/20 to 2021/03/16; (b) 2021/03/17 to 2021/05/01; (c) 2021/05/02 to 2021/07/01; and (d) 2021/07/02 to 2021/08/31. It is likely that the dashed boxes of the same color denote the chain of commercial trips over four periods. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

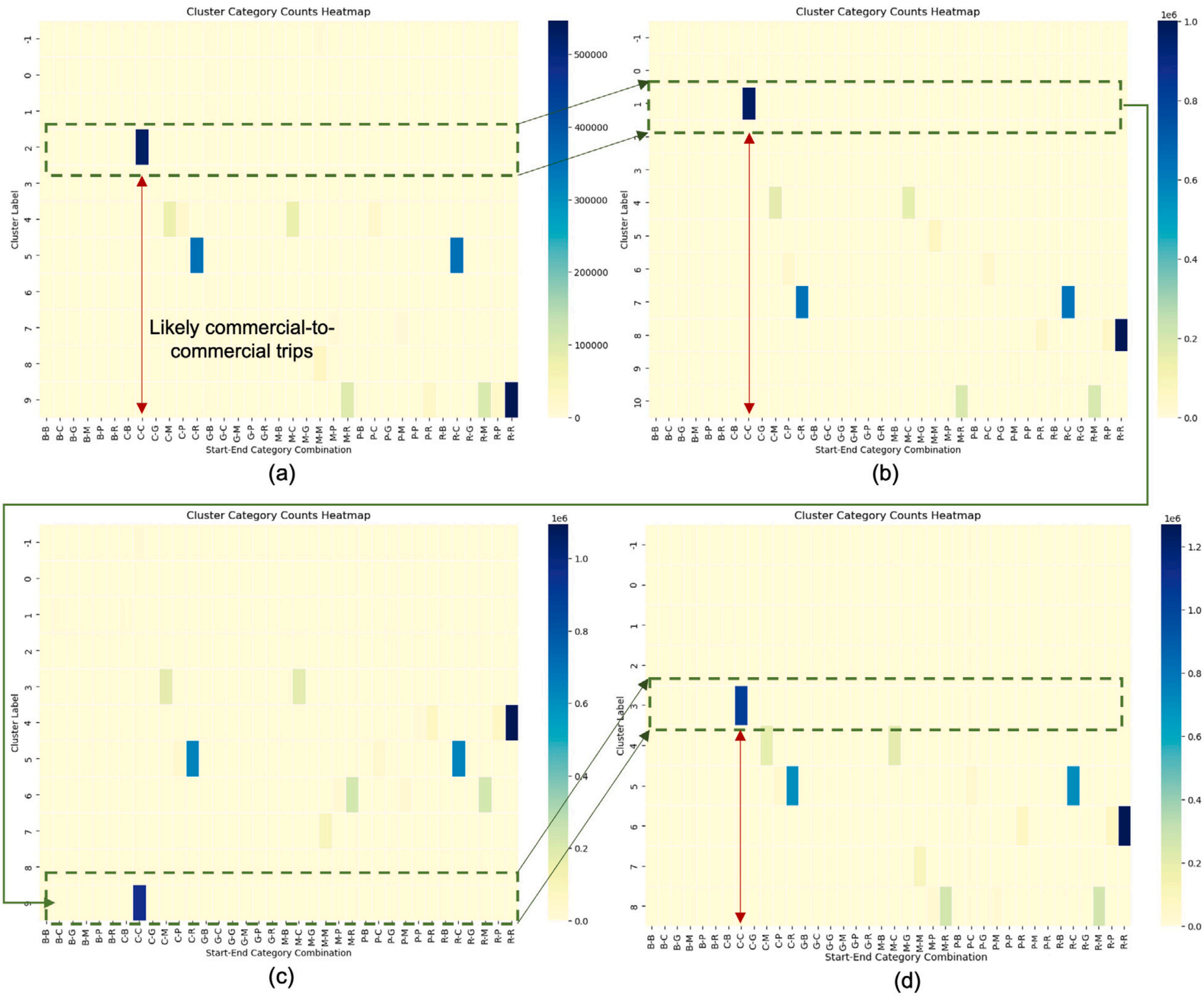

Fig. A.2. The breakdown of the number of trips according to the land use types at origins and destinations for each cluster label during the fixed four periods in 2022: (a) 2022/01/20 to 2022/03/16; (b) 2022/03/17 to 2022/05/01; (c) 2022/05/02 to 2022/07/01; and (d) 2022/07/02 to 2022/08/31. It is likely that the dashed boxes of the same color denote the chain of commercial trips over four periods. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

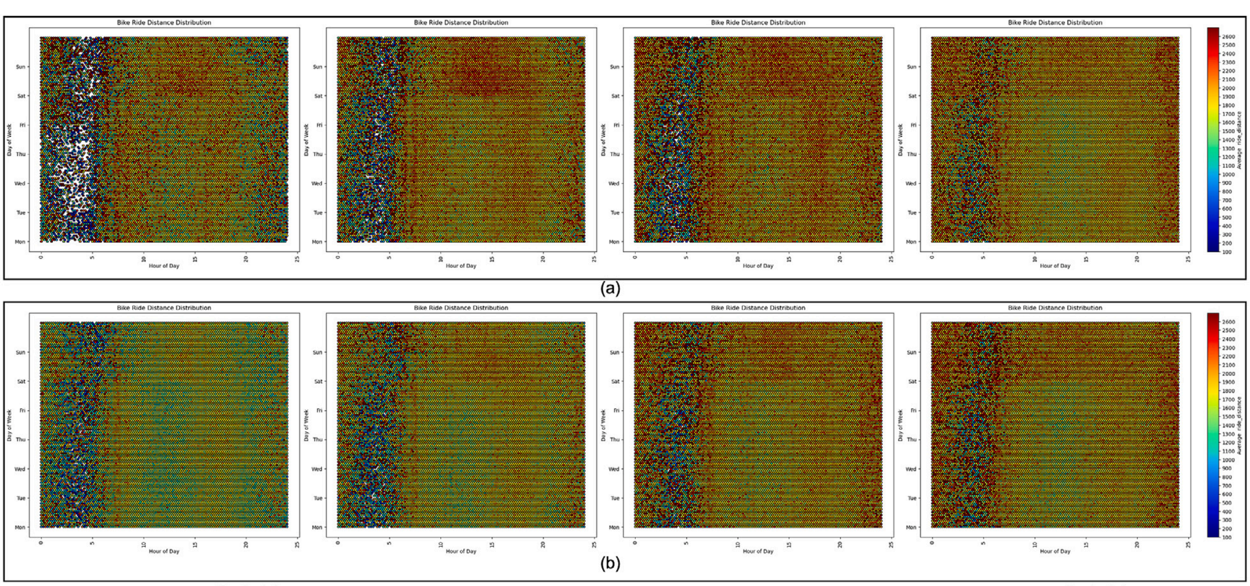

Fig. B.1. The time-of-the-day patterns of the average distance of residential-to-residential trips over four periods in (a) 2021 and (b) 2022. Left to right - from periods 1 to 4.

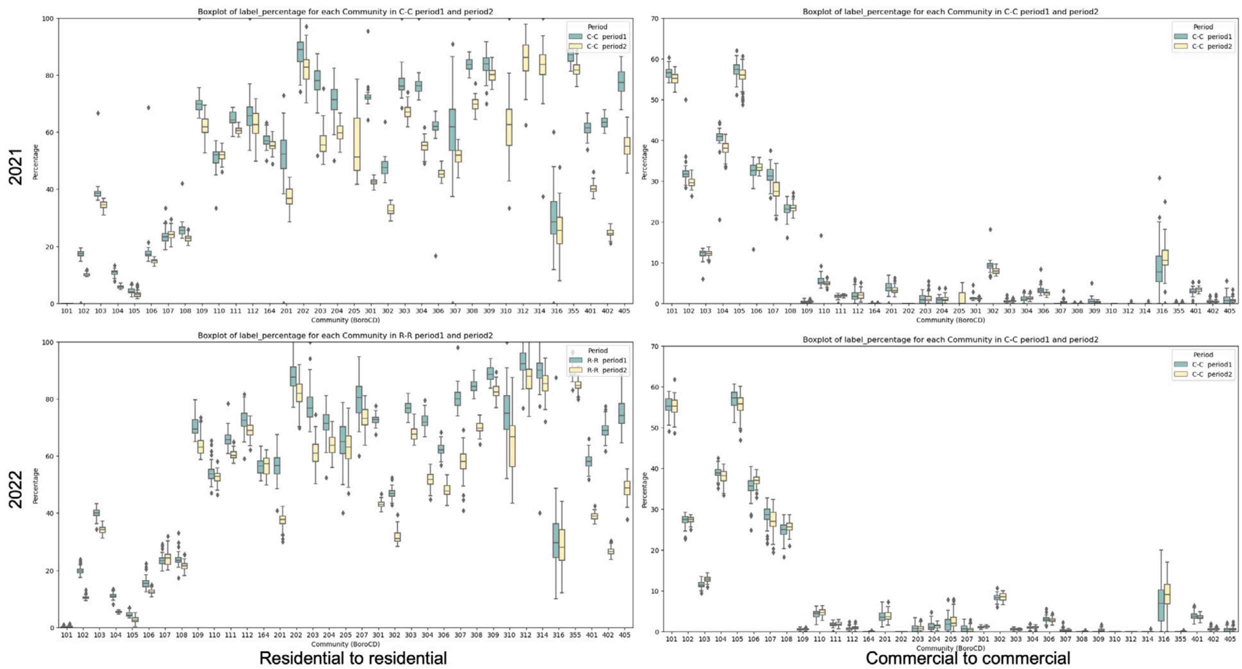

Fig. C.1. Boxplots of the percentage of bike-sharing trips of different communities in period 1 (from January 20 to March 16) and period 2 (from March 17 to May 1). First column - residential-to-residential trips; Second column - commercial-to-commercial trips; First row - 2021; Second row - 2022.

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