Spatio-temporal analysis of COVID-19's impact on human mobility in NYC

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1 Introduction

Since the World Health Organization declared the novel coronavirus (COVID-19) outbreak a global pandemic on March 11 2020, the disease has influenced every part of people's daily life and caused more than six million deaths globally (Johns Hopkins Coronavirus Resource Center, 2022). Mobility pattern tracks human movement behavior, which is critical to understand, evaluate and predict the pandemic transmission Commuting and large-scale gathering aggravate pandemic transmission, at the same time the pandemic transmission prevents social activity and lowers travel behavior. Thus, many non-pharmacological policies such as quarantines, travel restriction, social distancing have been implemented by governments to prevent the spread of COVID-19.

As the most populous city in the United States with 8.8 million people distributed over 300.46 square miles (U.S Census Bureau, 2020), New York City has experienced rapid and widespread transmission since the first confirmed case on March 1st 2020. At the end of March 2020, NYC arrived at the peak of COVID-19 and became the pandemic epicenter (Cordes & Castro, 2020) with a weekly mean of 5132 diagnosed cases and 1,566 hospital admissions. On March 22, 2020, 'New York State on PAUSE' executive order was declared. It includes a new directive that all non-essential businesses statewide must close in-office personnel functions effective (New York State Office, 2020). Identifying the spatio-temporal changes of human mobility pattern before, during and after the outbreak of COVID-19 is important in order to analyze COVID-19's impact on individuals. In addition, analyzing mobility changes under the contextual backgrounds suggests the heterogeneity of COVID-19's impacts on different groups. For example, high-income individuals may choose to decrease their visits to wholesale markets and restaurants and buy takeaways services to access necessary foods. However, people with low- or moderate- incomes may have no choice but to leave home to buy food with higher risk of infection.

Therefore, the objective of this paper is to study the spatio-temporal changes of mobility pattern in NYC in March 2019, March 2020 and March 2021 and analyze the social equity issues caused by the pandemic. The research is aimed to answer the following questions:

1. What is the spatial shifting pattern of visit counts to different business categories?
2. What is the temporal change of mobility pattern before, during and after COVID-19?
3. How does COVID-19 influence individual's travel behaviors in different contexts?

Figure 1: Study Area

2 Data

The mobility information was provided by the pattern datasets and core place dataset from SafeGraph. SafeGraph is a data company that aggregates anonymized location data from third-party applications. Core place dataset are defined as any location humans can visit with the exception of single-family homes with 84717 point of interests (POI) in total, which encompasses a diverse set of places ranging from restaurants, grocery stores, and malls; to parks, hospitals, museums, offices, and industrial parks (SafeGraph, 2022). Pattern dataset records the block-group-level mobility information such as visitor and visit counts to each POI. However, the datasets from SafeGraph does not cover all actual visitors but rather a subset of users that have smartphones and enabled their GPS information in various apps (Sevtsuk, 2021).

Socio-economic information such as race and income was from the American Community Survey (ACS) 2015-2019 5-year data.

In addition, the geographic base map was from the US Census Bureau's TIGER 2020 Census Tracts (clipped to shoreline) data products.

Data	Geographic Level	Source
Mobility Pattern in March 2019	Block Group	SafeGraph
Mobility Pattern in March 2020	Block Group	SafeGraph
Mobility Pattern in March 2021	Block Group	SafeGraph
Core Place	Block Group	Block Group
Demographic Data (e.g. income, race)	Census Tract	ACS 2019 5-year data
Geographic boundary	Census Tract	US Census Bureau

Table 1: Data source

3 Methods

3.1 Spatio-temporal analysis

Firstly, the monthly mobility pattern data in March in 2019, 2020 and 2021 were collected from SafeGraph and merged with core place dataset to get information about the POI's location and naics code. The merged data were aggravated to the tract level and mapped as polygon with geometry data from the U.S. Bureau. All Data processing steps were finished by Python 3.80.

Secondly, spatial distribution of people's visits to public places in NYC was analyzed with global and local Moran's I. Moran's I is a correlation coefficient to measures the similarity in neighboring places defined as Equation (1) (Moran, 1950). Large positive Moran's I (close to 1) indicates that strong positive auto-correlation and areas with similar values cluster together. Large negative values (close to -1) indicate strong negative auto-correlation and areas with dissimilar values cluster together.

$$\frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2} \tag{1}$$

In Equation (1), n is the number of observations. X_i is the visit count at census tract i. X_j is the visit count at another location j. $\bar{X}$ is the mean value. w_{ij} is the spatial weights between place i and place j. If places i and j are neighbors, w_{ij} is close to 1; while they are not neighbors, w_{ij} equals zero. Neighbors are defined by queen criterion, which are places that share a common boundary or vertex. Global Moran's I was calculated to examine the existence of spatial clustering in visit count. Local Moran's I was calculated to evaluate the extent of spatial auto-correlation between place i and its vicinity. The significance assessment was calculated by pseudo p-value with 999 random permutation. All spatial auto-correlation analysis was calculated by using GeoDa 1.20.

The temporal changes of visit count between March 2019, March 2020 and March 2021 was calculated as Equation (2):

$$\text{change percentage } = \begin{cases} \frac{v_{t_1} - v_{t_0}}{v_{t_0}} \times 100\%, & v_{t_0} \neq 0 \\ \text{inf}, & v_{t_0} = 0 \end{cases} \tag{2}$$

3.2 Business type analysis

The temporal changes of visit count between March 2019, March 2020 and March 2021 calculated by Equation (2) was analyzed in business types.

3.3 Socio-economic analysis

Associations between temporal changes of visit counts and contextual socio-economic factors at tract level were evaluated by descriptive spatial analysis and correlation analysis. The dependent variables included the percent change of inflow visits (the number visit counts flowing into a specific tract from all other places) and outflow visits (the number of visit counts from a specific home tract to all other places). Wrangling from ACS 2019 5-year data, independent variables such as proportion non-Hispanic white, proportion non-Hispanic black, proportion non-Hispanic Asian, proportion Hispanic, proportion of population with at least bachelor's degree, proportion of vacant units, average household car ownership and average household median income were collected. First, the original-destination matrix was built based on the visitors' home tract id and POI's tract id. Then, the O-D pair was merged with ACS data. Third, the explanatory was conducted to analyze the correlationship between predictors and independent variables and correlation between predictors. Maps were created to show the human mobility in income context. In addition, Pearson correlation coefficient were computed to indicate the relationships between predictors and dependent variables with significance levels of $p < 0.05$.

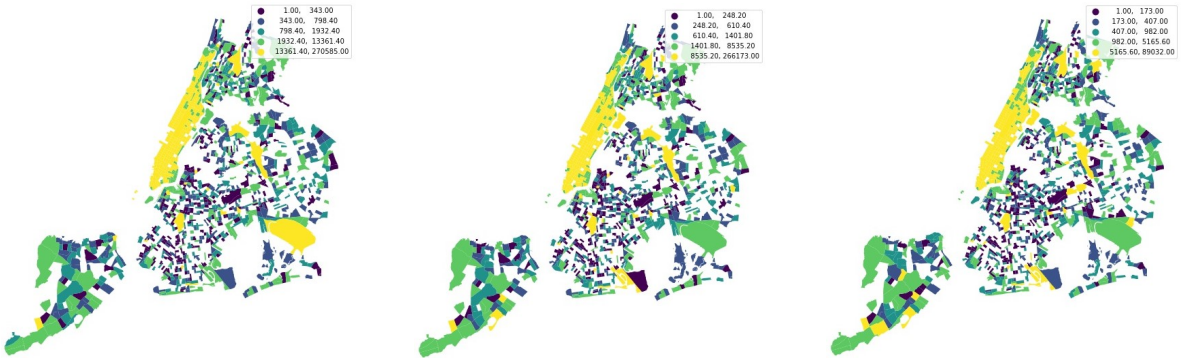
$$\text{comparison of change degree between high-/low- income} = \begin{cases} \left(\frac{v^H_{i,t_1} - v^H_{i,t_0}}{v^H_{i,t_0}} - \frac{v^L_{i,t_1} - v^L_{i,t_0}}{v^L_{i,t_0}}\right) \times 100\%, & v_{t_0} \neq 0 \\ \text{inf}, & v_{t_0} = 0 \end{cases} \tag{3}$$

In Equation (3), i is the destination tract. v^H_{i,t_0} is visit count from the original tracts where the income are higher than the average income in NYC to destination i at t_0 time, and v^L_{i,t_0} is visit count from the original tracts where the income are lower than the average income in NYC to destination tract i at t_0 time, and $t_1 \geq t_0$.

4 Results

4.1 Spatio-termporal analysis

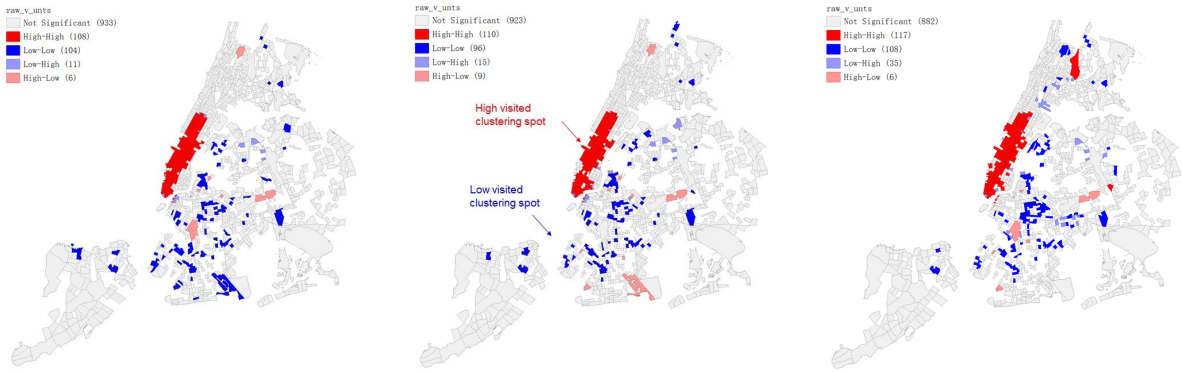
Choropleth maps for the total visits in NYC shows that Manhattan, John F. Kennedy (JFK) International Airport, LaGuardia Airport are the places people visit most often.



(a) March 2019 (b) March 2020 (c) March 2021

Figure 2: Visit count in different years

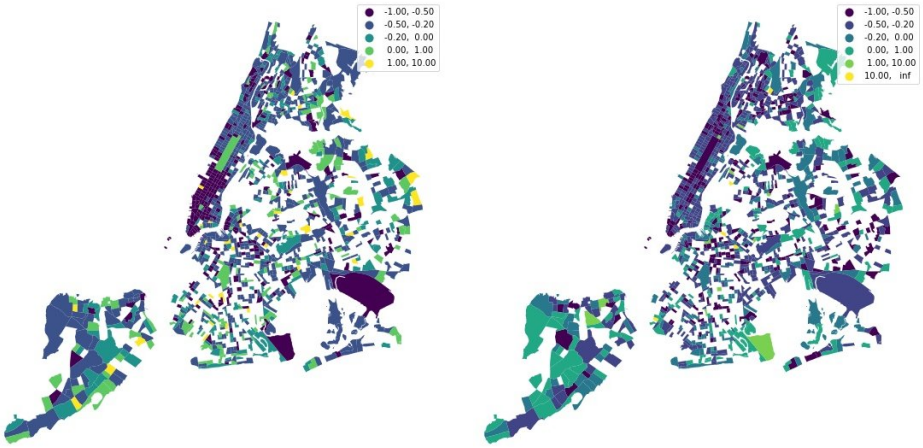
The global Moran's I values of visit count in 2019, 2020 and 2021 are statistically significant, indicating strong clustering pattern in human mobility. The result of local Moran's I is presented in Figure 3. According to the map, the clusters of high visited areas in 2019 were located at Central Park, Midtown and Lower Manhattan, while the clusters of low visited areas were spread in Brooklyn and Queens Boroughs. However, in 2021, northwestern area at the Bronx borough became the high-visit-count spot.



(a) March 2019 (b) March 2020 (c) March 2021

Figure 3: Clustering map with local Moran's I statistics

Choropleth maps for the visit count change percentage in NYC shows that people continued to decrease their activities in the later two years. Particularly, people have decrease their visits to Lower Manhanttan and JKF International Airport, LaGuardia Airport and Floyd Bennett Field in southeast Brooklyn Borough by 50%-100%. However, people did increase their visits to Central Park in Manhanttan Borough during the COVID-19. In March 2021, visits to Staten Island and Woodlawn Heights in Bronx Borough. Woodlawn Heights is a predominantly Irish-American working class neighborhood at the north end Bronx Borough. Compared to March 2020, visits to Central Park, LaGuardia Airport and New York Library at Staten Island has decreased mostly, while visits to other places in Manhattan also had a 50%-0% drop.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 4: Percent change of visit count to Education

4.2 Business type analysis

Visits to public places has continually decreased from March 2019 to March 2021. Specifically, visits to professional and business services, accommodation, food wholesale and retail stores decreased more than 50% from March 2019 to March 2020. This significant decrease trend extends to March 2021 for transportation transit and accommodation places. Since education, transportation, food, wholesale and retail and health cares are necessary goods and services, the following sections describe the spatio-temporal changes of human mobility in these business categories in detail.

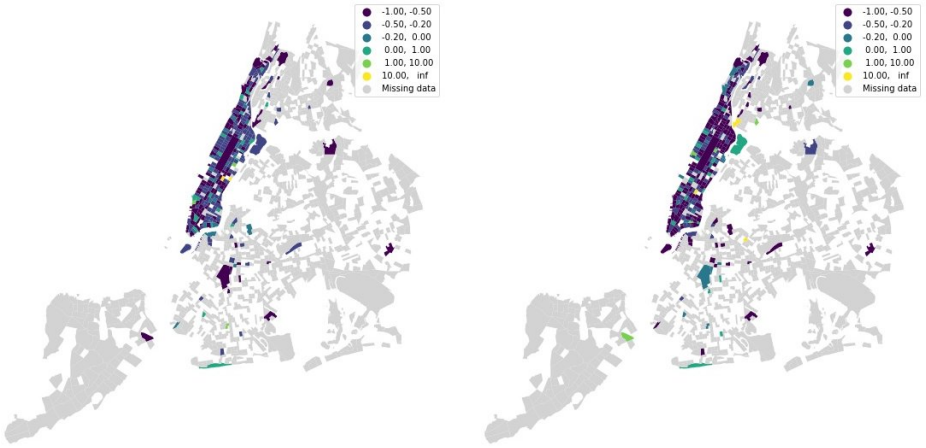
Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Accomodation	467745	196575	96993	-58%	-51%
Education	395591	221494	111892	-44%	-49%
Financial Activities	10235	6117	3658	-40%	-40%
Food	4887715	2122903	1214377	-57%	-43%
Goods Production	103881	52777	26788	-49%	-49%
Health Care	491347	321706	219743	-35%	-32%
Other	162728	95766	61500	-41%	-36%
Professional and Business Services	44009	17041	10561	-61%	-38%
Real Estate	139983	78127	53808	-44%	-31%
Recreation	4084598	3228826	2065839	-21%	-36%
Transportation	192828	95832	48065	-50%	-50%
Wholesale and Retail	2713860	1317471	795016	-51%	-40%

Table 2: Changes in different business categories

4.2.1 Education

As Mayor Bill de Blasio announced the 2-week all-remote learning in public schools from March 20 2020 in NYC, visits to education POI has decreased significantly. Most schools in Manhattan Borough show a 20%-50% decrease in visit counts in March 2020, and schools at Central Park such as Harlem

Chess Center had a more than 50% decrease in March 2020. From 2020 to 2021, the decreasing rate of visit count to school expanded to over 50% in Upper Manhattan.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 5: Percent change of visit count to Education

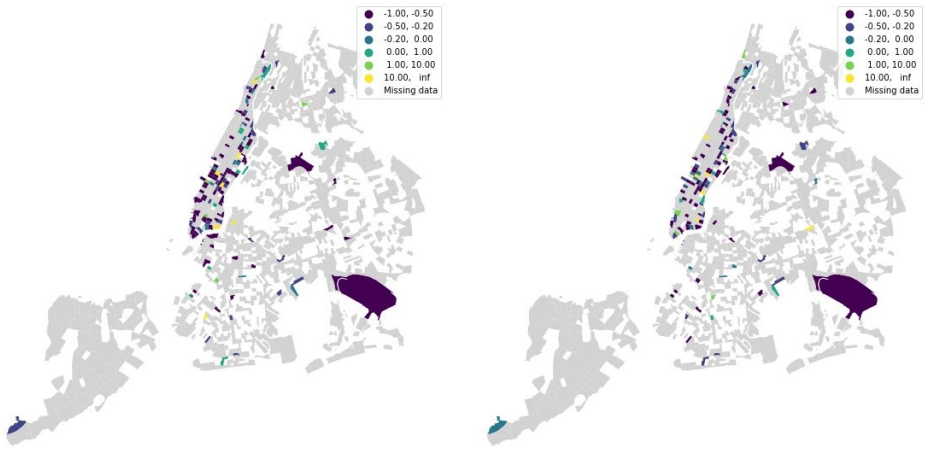
Visits to schools decreased by 42% from 2019 to 2020 and 49% from 2020 to 2021. Particularly, visits to elementary and secondary schools which constitutes kindergarten through 12th grade show a 41% reduction from 2019 to 2020, and a 49% reduction from 2020 to 2021. In addition, visits to higher education dropped by 49% in March 2020. Technical schools include junior colleges, automobile driving schools, cosmetology and barber schools and other technical and trade schools. Visits to technical schools saw a 58% decrease from 2019 to 2021.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Colleges, Universities, and Professional Schools	23102	11702	5985	-49%	-49%
Elementary and Secondary Schools	291072	171292	87885	-41%	-49%
Technical School	7620	3160	1312	-59%	-58%
Total visit count	340251	196646	100045	-42%	-49%

Table 3: Percent change in education subcategories

4.2.2 Transportation

Visits to POI in transportation places decreased by 75% in March 2021, compared to the time before COVID-19, with more than 50% fewer visits to JFK International Airport and LaGuardia Airport as observed in 2020, and decreasing by about 50% in 2021.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 6: Percent change of visit count to Transportation

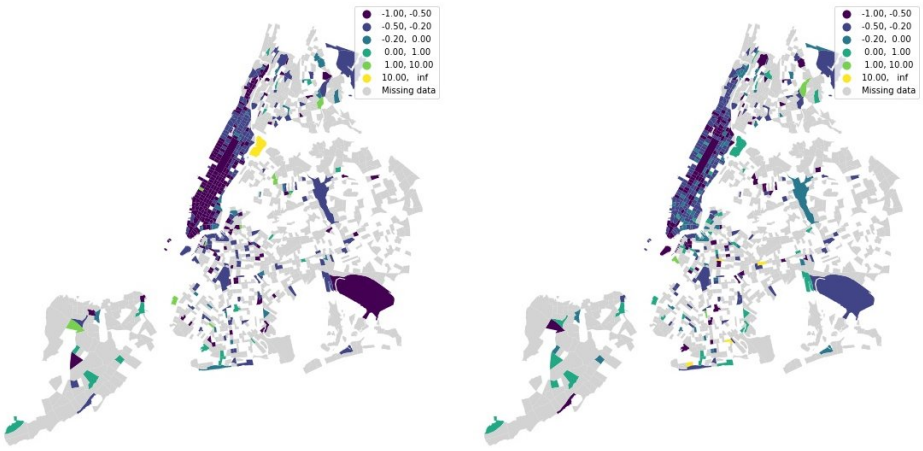
Visits to transportation system has decreased by 50% from 2019 to 2020 and from 2020 to 2021. Particularly, visits to airport has decreased by 53% from 2019 to 2020 and decreased by 52% from 2020 to 2021. Visits to bus and other motor vehicle transit system had a noticeable 68% decrease in 2020 and a smaller 12% reduction in 2021. Visits to line-hail railroads was decreased by 40% in the first year of COVID-19, and remained 40% decreasing rate from 2020 to 2021. However, contrasting to the general decreasing trend, water vehicle transportation saw a increase from 2019 to 2020. For example, the visits to port and harbor operations increased 10 times from 2019 to 2020. However, from 2020 to 2021, the count decreased to value in 2019. In addition, from 2019 to 2020, visits to inland water passenger transportation increased by 12%. However, from 2020 to 2021, it decreased by 45%.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Airport	178839	84109	40778	-53%	-52%
Line-Haul Railroads	3821	2281	1398	-40%	-39%
Bus and Other Motor Vehicle Transit Systems	4136	1318	1166	-68%	-12%
Port and Harbor Operations	187	2073	186	1009%	-91%
Inland Water Passenger Transportation	883	992	549	12%	-45%
Total visit count	192334	95329	47437	-50%	-50%

Table 4: Percent change in transportation subcategories

4.2.3 Food

The spatial distribution of change of visits to POI in food shows that people decreased their visits to food places from 2019 to 2020 and 2021 in general. Particularly, visits to POI in food near Central Park, Midtown Manhattan and Lower Manhattan, and JFK international airport had a significant decrease with less than 50% visits to Upper Manhattan, Brooklyn Borough and Central Woodlawn at the north end of the Bronx Borough decreased by 20% -50%. From 2020 to 2021, the degree of decreasing had slowed down for most areas in NYC, although the visits to restaurants near Central Park continued to show a 50% drop. Visits to restaurants at JFK international airport decreased by 35.6% in 2021. Visits to Flushing Meadows Corona Park in northern Queens Borough decreased by 33.2% from 2019 to 2020, however, only decreased by 5% from 2020 to 2021.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 7: Percent change of visit count to Food

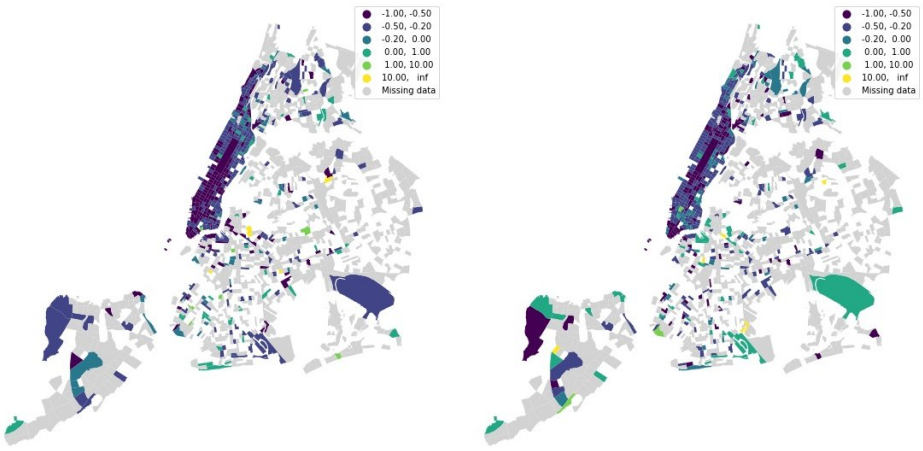
Visits to places in food has decreased by 57% from 2019 to 2020 and with smaller drop from 2020 to 2021: about 44%. Particularly, visits to drinking places, full-service restaurants and limited-service restaurants(e.g. fast-food restaurants and takeout eating places) all show a 59% decrease from 2019 to 2020.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Caterers	52018	23190	13177	-55%	-43%
Drinking Places (Alcoholic Beverages)	547215	223974	131639	-59%	-41%
Full-Service Restaurants	1989470	816758	491380	-59%	-40%
Limited-Service Restaurants	1031002	419592	227798	-59%	-46%
Snack and Nonalcoholic Beverage Bars	926039	462201	235293	-50%	-49%
Total visit count	4545744	1945715	1099287	-57%	44%

Table 5: Percent change in food subcategories

4.2.4 Wholesale and Retail

The spatial distribution of change of visits to POI in wholesale and retail shows that people decreased their visits to wholesale and retail stores and supermarkets from 2019 to 2020 and 2021 in general. From 2019 to 2020, visits to POI in such category has decreased by more than 50% in Central Park and Midtown and Lower Manhattan. Visits to Upper Manhattan, West Shore in Staten Island Borough, JFK international airport and north areas in Bronx Borough decreased by 50% -20%. From 2020 to 2021, visits to POI in wholesale and retail decreased by 50% near Central Park in Manhattan Borough and West Shore in Staten Island Borough. However, the decreasing rate to other places in NYC has dropped. In addition, visits to wholesale and retail in JFK has increased by 20% in 2021.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 8: Percent change of visit count to wholesale and retail

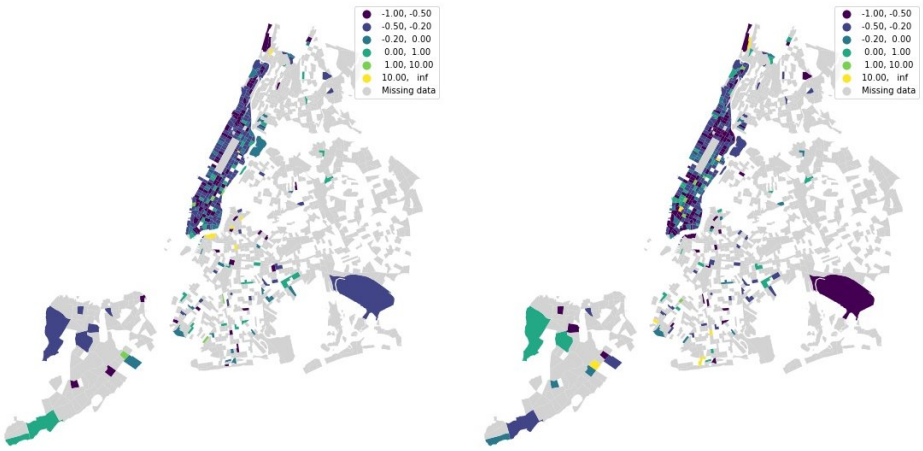
Visits to places in wholesale and retail has decreased by 34% from 2019 to 2020, and decreased by 41% from 2020 to 2021 in total. Particularly, from 2019 to 2020, visits to supermarkets and grocery retailers(except convenience retailers) had decreased by 33%. Visits to fruit and vegetable retailers, and drug merchant wholesale decreased by more than 40% in 2020. In 2021, the mobility pattern finds a 43% decrease in visits to supermarket and grocery, and a 35% reduction in visits to fruit and vegetable stores decreased by 35% in 2021. However, visits to drug merchant wholesale shows a trivial 2% increase from 2020 to 2021.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Drugs and Druggists' Sundries Merchant Wholesalers	1193	618	628	-48%	2%
Fruit and Vegetable Retailers	14857	8315	5379	-44%	-35%
Supermarkets and Other Grocery Retailers (except Convenience Retailers)	114498	77034	43662	-33%	-43%
Total visit count	167629	110027	64228	-34%	-42%

Table 6: Percent change in wholesale and retail subcategories

4.2.5 Health Care

The spatial distribution of change of visits to POI in heath care shows that people decreased their visits to heath care hospitals, facilities, and caring centers from 2019 to 2020 and 2021 in general. From 2019 to 2020, visits to POI in such category has decreased by 0-50% in Manhattan Borough, JFK international airport and western areas in Staten Island Borough. However, visits in hospitals at southeastern Staten Island Borough shows a 19.3% increase. From 2020 to 2021, visits to POI in health care shows a similar decreasing pattern in Manhattan Borough. However, visits to JFK international airport decreased by 60%. At the same time, visits to west shore in Staten Island Borough increased by 15.6%, while visits to southeastern Staten Island Borough shows a 27% decrease.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 9: Percent change of visit count to health care

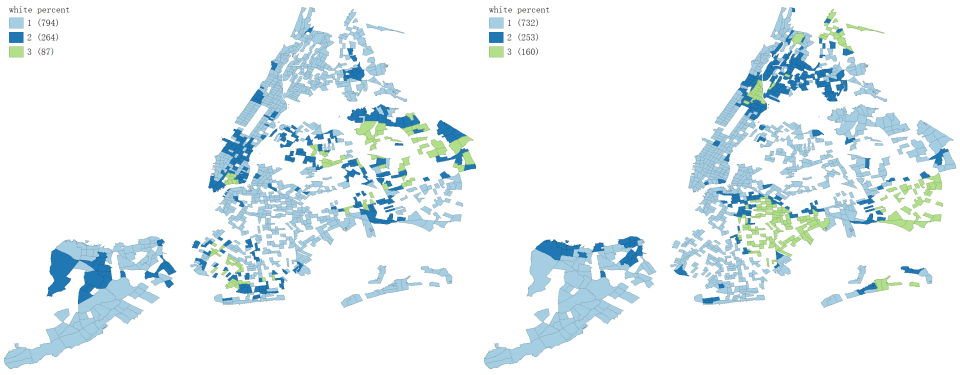
Visits to places in health care has decreased by 35% from 2019 to 2020, and decreased by 32% from 2020 to 2021. Especially, from 2019 to 2020, visits to nursing care centers(e.g. convalescent hospitals) and Physicians' office have decreased by more than 40%. Visits to child care hospital and services has decreased by 35%. However, in 2021, the visit count to child care services dropped by 48% compared to 2020. And the visit to nursing care facilities also dropped by 44%.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Child Care Services	89217	58072	30109	-35%	-48%
General Medical and Surgical Hospitals	148910	105307	83648	-29%	-21%
Kidney Dialysis Centers	40091	28468	18973	-29%	-33%
Offices of Physicians (except Mental Health Specialists)	82857	49998	35717	-40%	-29%
Nursing Care Facilities (Skilled Nursing Facilities)	5338	2983	1660	-44%	-44%
Total visit count	471345	307228	210259	-35%	-32%

Table 7: Percent change in health care subcategories

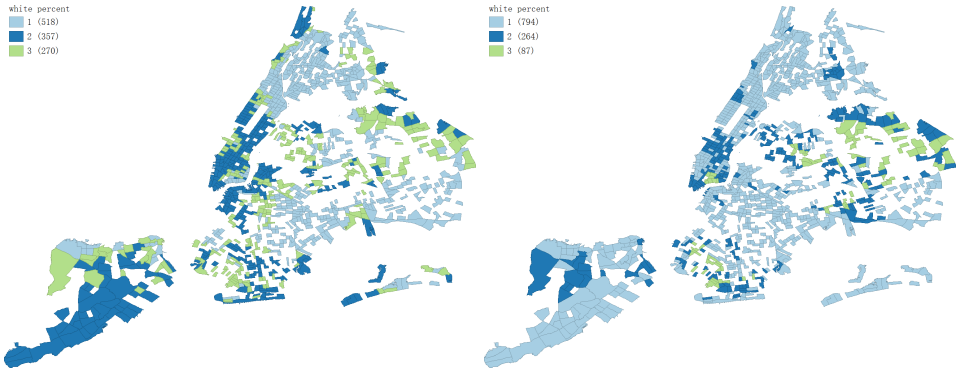
4.3 Social-economy analysis

The temporal changes of human mobility in different contexts at tract level was assessed to analyze COVID-19's impact on social equity by spatial and correlation analysis.



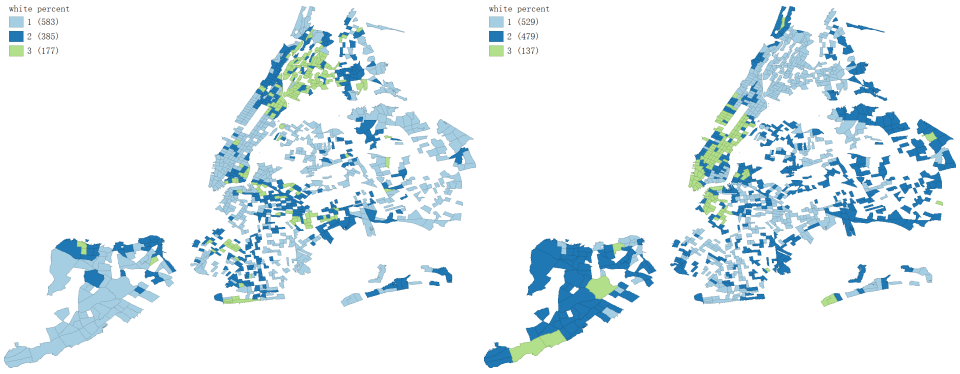
(a) Asian percent

(b) Black percent



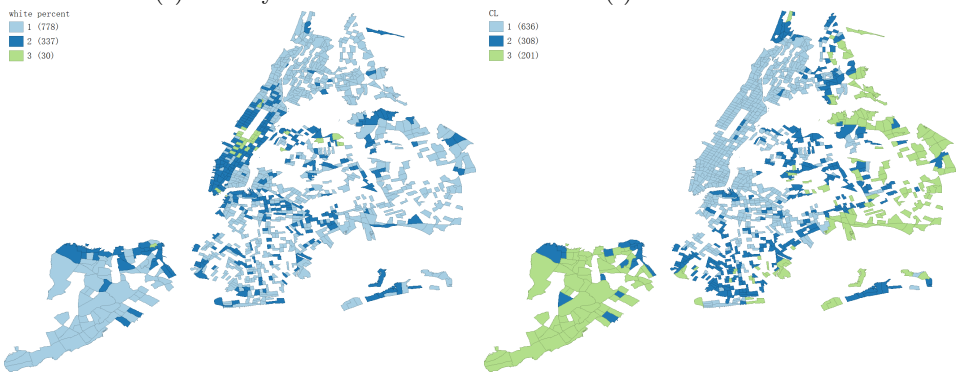
(c) White percent

(d) Hispanic percent



(e) Poverty rate

(f) Household income



(g) Vacant rate

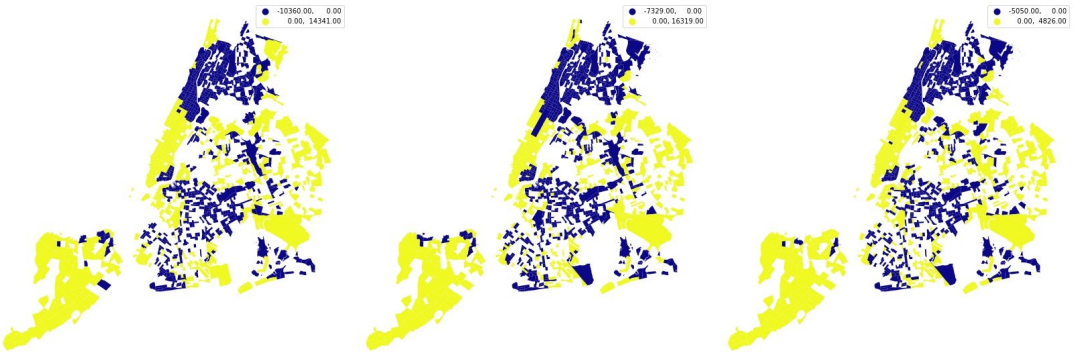
(h) Car ownership

Figure 10: K-means clustering of socio-economic factors, 1 represent low clustering and 3 represent high value clustering

4.4 Spatial Analysis

Human mobility pattern in NYC was analyzed in income contexts. High-income groups represent people living in the tracts where the local income is at the top quartile level in NYC. Low-income groups represent people living in the tracts where the local income is at the bottom quartile level in NYC.

First, the comparison of visit count in low- and high- income groups were analyzed in Figure (11). The blue areas are places where were more often visited by low-income residents. The yellow areas represent places where were visited more by high-income residents. Combined with clustering pattern of socio-economic factors, high-income groups were observed to have more visit to Lower Manhattan, Staten Island and outskirt of Queen Borough, where are places with high proportion of white race, high household income. Particularly, Lower Manhattan and north Staten Island have high vacant rate, and Staten Island as well as outskirt of Queen Borough have high car ownership. Low-income groups tend to have more visits to Upper Manhattan, Bronx Borough, Brooklyn Borough and south Queen Borough. There are places with high clustering of racial minority, and relative high poverty rate, andlow household income.



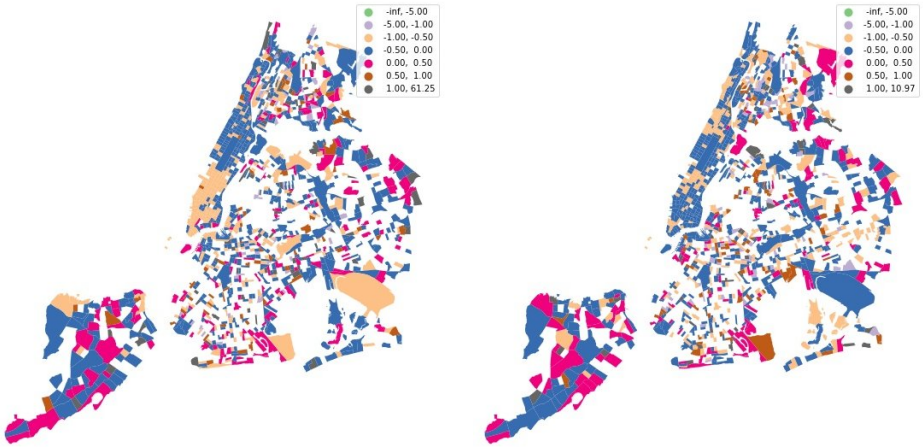
(a) March 2020 (b) March 2020 (c) March 2021

Figure 11: Comparison of visit count between high-income group and low-income group

Second, the change percent of visit count in high income groups were analyzed according to Equation (2). A general decrease trend in visit count in all income groups was observed from 2020 to 2021.

In March 2020, high-income groups visited Lower Manhattan, JFK International Airport and LaGuardia Airport at Queens Borough with a over 50% decrease in frequency. At the same time, their visits had 0-50% decrease to Upper Manhattan, west shore, northern and eastern areas in Staten Island Borough. However, there was an increase in visit count to Staten Island and outskirt of southeast shore of Brooklyn and north end of Queens Borough in March 2020.

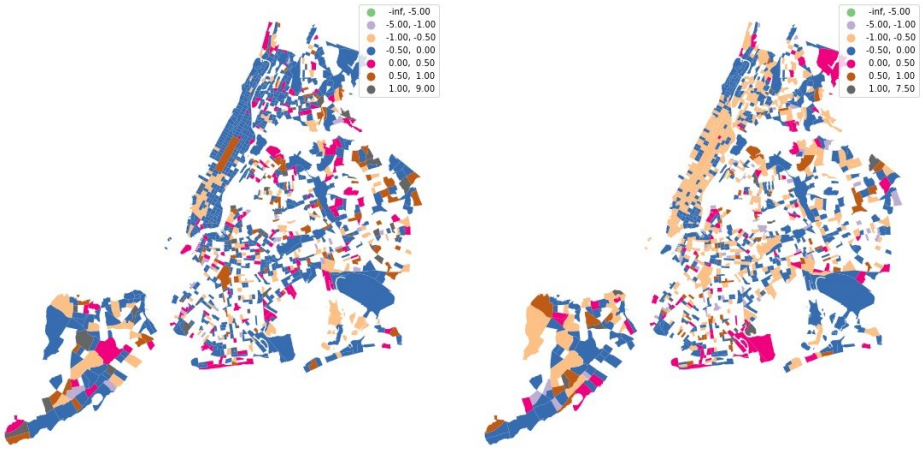
In March 2021, high-income groups had a 0-50% decrease in visit counts to Central Manhattan, west shore, northern and eastern areas in Staten Island Borough. However, increases were observed in Staten Island and northeastern Bronx Borough. A significant 50%-100% increase in visit counts was found in Floyd Bennett Field in southeast Brooklyn Borough. In addition, people's visits to central Staten Island and northeastern Bronx Borough increased by 0-50%.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 12: Percentage change of visit count of people from top quartile income tract

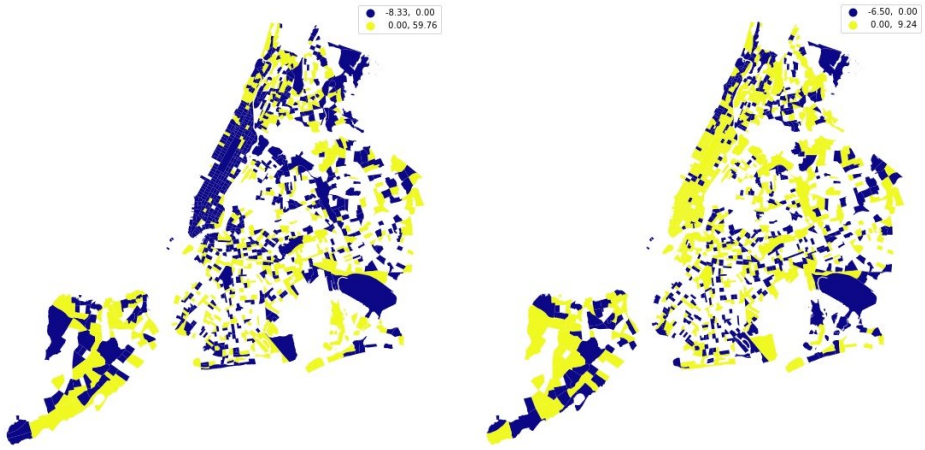
As for low-income groups, there were a wider coverage of human mobility compared to high-income groups. Particularly, their visits to Manhattan, JFK, and Pleasant Plains neighborhood in south Staten Island Borough dropped by 50%-100% in 2020. Visits from this group to Lower Manhattan decreased by over 50%. However, visits to Central Park increased by 95.3%. In addition, visits to two neighborhoods in south and east shore in Staten Island Borough increased by 100%. In 2021, the decreasing rate of visit count from low-income tracts in Manhattan was larger than 50%. For example, people's visits to Central Park has decreased by 84.5% compared to last year.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 13: Percentage change of visit count of people from bottom quartile income tract

Third, the change degree of visit count in different years in low- and high- income groups were analyzed according to Equation (3) and showed in Figure (14). The blue color means the difference of visit change percentage between high- and low- income group difference is negative, and the yellow color represents the difference is positive. From 2019 to 2020, the difference of visit count change percentage between high- and low- income groups in most areas in Manhattan, JFK and Staten Island are negative, indicating low-income groups decreased their visits to these areas in smaller degree during the outbreak of COVID-19. From 2020 to 2021, the difference of visit count percentage between high-income to low-income groups change are positive in most areas, indicating low-income groups decreased their visits to most places in New York in larger degree.



(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 14: Comparison of the percentage change between high-income group and low-income group

4.5 Correlation Analysis

Correlation coefficients were computer to indicate the relationships between the temporal change of visit counts in March 2019 and March 2020 and socio-economic variables including median household income, race composition, vacancy rate, education attainment, poverty rate and car ownership .

With significance levels of $P < 0.05$, the proportion of White, and average number of car in household have positive correlation with change of outflow visit count between March 2019 and March 2020. Proportion of vacant units, proportion of people with at least bachelor's degree, and median household income have negative correlation with outflow visit count change. This indicates areas with low proportion of white race, low proportion of car ownership, high vacant rate, high education attainment and high median household income tend to large decrease in visiting other places in NYC during COVID-19.

As for the correlation analysis between **inflow** visit count change and socio-economic factors, the household average number of car was found have sttrong positive correlation with visit counts. Proportion of vacant units, proportion of people with at least bachelor's degree, median household income and poverty rate tend to have negative correlation with visit count change. This indicates people tend to decrease their visits to areas with high vacancy rate, high poverty rate and high education attainment, high median household income and low car ownership rate during the pandemic.

Variables	Outflow visit count		Inflow visit count change	
	coefficient	P value	correlation	P value
Constant	-418.067	**0.01019**	14086	**0.00000**
Proportion of White	293.732	**0.02520**	2543.8	0.28115
Proportion of Black	171.007	0.13439	-654.387	0.78485
Proportion of Indian	-338.203	0.92379	-1583.32	0.98036
Household Car Ownership	1024.31	**0.00000**	6385.25	**0.00000**
Vacancy Rate	-1503.85	**0.00073**	-64113	**0.00000**
Poverty Rate	-358.032	0.30601	-21036	**0.00007**
Percent of Bachelor Degree	-17604.1	**0.00000**	-150572	**0.00000**
Median Household Income	-0.0103247	**0.00000**	-7629.32	**0.01476**

Table 8: Correlationship for predictors and visit count change between March 2019 and March 2020. Bold values are significant at $P < 0.05$.

5 Discussion

This study characterizes the spatial distribution and temporal shifting of human mobility before, during and after COVID-19, as well as compares the change rate in socio-economic contexts to analyze social equity issues. Decrease was found in most places in NYC after the outbreak of COVID-19 and this trend was observed to be sustained in March 2021. Particularly, visits to necessary goods and services such as transportation, education, health care, wholesale and retail, as well as food saw a significant decrease.

Manhattan Borough was found the most popular places all the time, even it experience largest degree in visit counts during the pandemic.

This study identifies that the disparity in the human mobility during the COVID-19. People tend to decrease their visits to low-income areas, which indicates the business in these neighborhoods were hit hardest during the first month of the COVID-19 by correlation analysis.

In addition, low-income groups tend to have more visits to low-income and low education attainment areas such as Upper Manhattan Borough, Bronx Borough and Brooklyn Borough according to Figure (11). These areas were found the most confirmed virus cases in March 2020(Buchanan et al., 2020).

High-income groups have more visits to Lower Manhattan, Staten Island. There was a significant increase in Staten Island and outskirt of southeast shore of Brooklyn and north end of Queens Borough. Most of these places are high-income, high education attainment and high vacancy rate areas. They were also found to have less confirmed case rate in the first month(Buchanan et al., 2020). Thus, we can conclude that high-income groups migrated to outskirt of the city during the outbreak of COVID-19.

All the information indicates that lower-income people suffer larger economic loss and higher risk of COVID-19 transmission due to mobility movement, which exposes the social inequity issues in NYC.

This study has limitation in data representativeness. The human mobility data from SafeGraph only captures small portion of total population considering only limited people would like to use mobile phone and enable the APP to upload GPS information. Thus, multi-source human mobility analysis needed to be conducted to illustrate the spatio-temporal heterogeneity in human mobility comprehensively(Noi et al., 2022).

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