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Understanding mobility change in response to COVID-19: A Los Angeles case study

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ABSTRACT

The COVID-19 pandemic has affected people’s lives throughout the world. Governments have imposed restrictions on business and social activities to reduce the spread of the virus. In the US, the pandemic response has been largely left to state and local governments, resulting in a patchwork of policies that frequently changed. We examine travel behavior across income and race/ethnic groups in Los Angeles County over several stages of the pandemic. We use a difference-in-difference model based on mobile device data to compare mobility patterns before and during the various stages of the pandemic. We find a strong relationship between income/ethnicity and mobility. Residents of low-income and ethnic minority neighborhoods reduced travel less than residents of middle- and high-income neighborhoods during the shelter-in-place order, consistent with having to travel for work or other essential purposes. As public health rules were relaxed and COVID vaccines became available, residents of high-income and White neighborhoods increased travel more than other groups, suggesting more discretionary travel. Our trip purpose model results show that residents of low-income and ethnic minority neighborhoods reduced work and shopping travel less than those of White and high-income neighborhoods during the shelter-in-place order. Results are consistent with higher-income workers more likely being able to work at home than lower-income workers. In contrast, low-income/minorities apparently have more constraints associated with work or household care. The consequence is less capacity to avoid virus risk. Race and socioeconomic disparities are revealed in mobility patterns observed during the COVID-19 pandemic.

1. Introduction

The COVID-19 pandemic has affected economies and people around the world. The first reported COVID-19 case was confirmed in China in December 2019, and the virus then spread quickly to the rest of the world. On March 11, 2020, the World Health Organization (WHO) officially declared COVID-19 a pandemic (WHO, 2020). The first confirmed case of COVID-19 in the US occurred in Snohomish County, Washington on January 21, 2020. The virus spread quickly across the country (Gao et al., 2020). By March 17, 2020, COVID-19 had been reported in all 50 states in the US (ABC News, 2020).

Given the absence of pharmacological control measures (e.g., medical treatment or vaccine) in the early stages of the pandemic, governments and health officials relied on non-pharmaceutical interventions to control the spread of the virus, including social distancing, use of face coverings, and shelter-in-place orders (Davies et al., 2020; Flaxman et al., 2020; Lai et al., 2020). In the US, social distancing was the primary strategy to limit the spread of COVID-19 until vaccinations became available in December 2020. In the absence of a strong federal response, managing the pandemic was largely left to state and local governments. Many states, counties, and cities began issuing shelter-in-place or similar mitigation measures that required residents to reduce movement and stay home as early as March 2020. Rules were relaxed as vaccinations became more available.

Variation in COVID-19 policies provides an opportunity to examine travel behavior in response to shelter-in-place and other COVID-19 prevention policies. Our interest is on disparities in mobility changes across socioeconomic groups. Many papers have now been written on the travel impacts of the pandemic. Evidence suggests that travel patterns of low-income and minority populations changed less than those of higher income populations. These results were linked to the greater likelihood that low-income and minority populations work in jobs that cannot be done remotely (Atchison et al., 2020; Brough et al., 2021; Clay and Rogus, 2021; Goldman et al., 2021). Our research contributes to this emerging literature in the following ways. First, we use smartphone mobility data to explore differences and responses across policy stages,
from the first shelter-at-home order to the widespread availability of vaccines. Second, we directly test the relationship between travel response and occupation by segmenting travel by trip purpose. Third, we use data at the census block level; previous studies of socio-economic effects have been conducted at census tract or larger geographies.

Our data covers Los Angeles County, one of the epicenters of COVID-19 in the US, from January 1, 2020, to April 16, 2021. This period includes a few months before the COVID surge in March 2020, three distinct policy stages and a period of vaccine availability. We use a difference-in-difference (DID) model to examine travel behavior across the various stages. We have two research questions: Do different race/ethnic or income groups respond differently to COVID-19 and related travel restriction policies? If so, what explains these differences? Prior research indicates that residents of low-income and minority-dominant neighborhoods are less able to comply with shelter-in-place orders relative to other groups due to differences in occupation (e.g. work in essential jobs that require physical presence) as well as racial and social segregation (Clay and Rogus, 2021; Hu et al., 2020; Khanijahani, 2022). However, these possible explanatory factors have not been formally tested. We compare travel behavior impacts across income and race/ethnic groups using two measures of mobility: total time spent at home, and average number of unique locations visited per day. We develop measures of trip purpose to examine whether differences across race/ethnic/income groups are associated with work or other more discretionary activities.

The remainder of the paper is organized as follows. Section 2 presents a brief review of the literature to date on COVID-19 travel impacts. Section 3 describes our data and methodology. Results are presented in Section 4. We provide conclusions and policy implications in Section 5.

2. Literature review

In this section we discuss the literature on (1) travel behavior changes in previous public health crises, and (2) travel behavior and COVID-19.

2.1. Travel behavior changes in previous health crises

Although there is no historical precedent for COVID-19 since the Spanish Flu of 1918, there is a literature on the effects of prior health crises such as SARS in 2003 and the H1N1 pandemic in 2009. Wen et al. (2005) analyzed the impacts of the 2003 SARS outbreak on the travel behavior of Chinese domestic tourists and found that the outbreak led to a dramatic decrease in travel and tourism. Liu et al. (2010) studied the effects of the SARS outbreak on air travel between the US and three destinations: mainland China, Hong Kong, and Taiwan. Their study showed that the impact and life cycle of SARS effect on air travel varied by location and health regulations. Both studies indicated that the decrease in travel was associated with a combination of travelers’ internal motivations (e.g., perceived risks) and external enforced measures (e.g., travel bans, stay-at-home orders, disclosure of epidemic information). Kim et al. (2017) analyzed transit smart card data in Seoul before and after the 2015 MERS outbreak. Individuals living in neighborhoods with higher land prices decreased their transit trips more than others, suggesting some influence of socio-demographics.

2.2. COVID-19 research

The scale and duration of COVID-19 may generate more dramatic and longer lasting impacts than have been observed with prior health crises. Research to date on COVID has addressed travel in various ways. Many papers have demonstrated the effectiveness of social distancing and shelter-in-place orders in reducing virus spread (Courtemanche et al., 2020; Fazio et al., 2021; Kwon et al., 2021). However, compliance varies across ethnicity and income levels (Barnett-howell and Mobarak, 2020; Chiou and Tucker, 2020; Wright et al., 2020). Recent literature shows that low-income and minority populations are less likely to shelter-in-place and have higher COVID infection and mortality than higher income populations and Whites (Chen et al., 2020; Hu et al., 2020; Jay et al., 2020; Khanijahani, 2022; Lou et al., 2020; Torrats-espinoasa, 2021). Explanations for these differences include financial constraints and occupation (Atchison et al., 2020; Blau et al., 2020; Clay and Rogus, 2021; Garfield et al., 2020; Goldman et al., 2021; Kar et al., 2021), racial segregation in residential neighborhoods, workplaces, and daily-life space (Hu et al., 2020; Khanijahani, 2022; Torrats-espinoasa, 2021), political preferences (Gatwood, 2021; Motta, 2020), and lack of trust in the medical profession (Stoler et al., 2021; Willis et al., 2021).

Lower income workers are less likely to be able to work remotely and more likely to have essential jobs in services, medical care, or retail that require physical presence and face-to-face contact (Atchison et al., 2020; Blau et al., 2020; Clay and Rogus, 2021; Garfield et al., 2020; Goldman et al., 2021). The lesser response to social distancing orders early in the pandemic is documented by Jay et al (2020) and Lou et al (2020) using smartphone mobility data. Both found that residents of low-income neighborhoods were more likely to work outside the home than residents of high income neighborhoods, supporting the explanation of occupation. Businesses deemed essential (e.g., grocery store, health facility) are staffed predominantly by low-wage and ethnic minority workers (Blau et al., 2020; Clay and Rogus, 2021; Garfield et al., 2020; Goldman et al., 2021).

Another way to reduce travel is to change shopping behavior. Kar et al. (2021) found that while many higher income people switched to online shopping and did more stock up during the COVID-19 pandemic, most low-income people did not have the means to shop online or stock up to reduce trips. To the extent that lower-income and ethnic minority workers continue to travel at higher rates, especially in modes frequently necessitating interaction with other people (e.g., public transit), higher viral transmission rates among those groups would be expected (Brough et al., 2021).

Other factors may also contribute to less compliance with COVID-19 policies among low-income and minority communities. Studies highlight the existing intersection of income and unequal access to information (Norris, 2001), differences in political preferences that may influence how information is processed (Feldman and Johnston, 2014; Gatwood, 2021; Motta, 2020) and attitudes toward risk (Milosh et al., 2020; Painter and Qiu, 2020; Yesuf and Bluffstone, 2009). In addition, there is evidence of lack of trust in the medical profession among people of color as a result of discrimination and poor quality medical care (Bogart et al., 2021; Jamison et al., 2019; Quinn et al., 2021).

There is a growing literature on mobility responses during the pandemic. However, gaps continue to exist. In the US, the pandemic response has been largely left to state and local governments (Gupta et al., 2021), yet most of the research has been conducted at the national level, making it difficult to examine responses to specific policies. Most existing literature concentrates on assessing how income disparities impact responses to the stay-at-home order (Jay et al., 2020; Lou et al., 2020; Weill et al., 2020) but does not consider the role of race and ethnicity. Most recent studies examined mobility change in response to non-pharmaceutical interventions (e.g., social distancing, face covering) during the pandemic (Brough et al., 2021; Fazio et al., 2021; Kwon et al., 2021; Mukherjee and Jain, 2022), but less is known about how people’s travel behavior and mobility change when COVID vaccines became available. We extend the literature by considering both income and race/ethnicity, using a time period that includes vaccine availability, examining mobility across different trip purposes, and using highly disaggregate data.

3. Methodology

3.1. Study area

Our study area is Los Angeles County, California, the most populous
Los Angeles County in the US, with over 10 million residents. It also has the highest average population density, 815 people/km² as of 2019. Los Angeles County is one of the most racially diverse in the US. There is no majority population. Hispanics¹ (49 % of the total population) are the single largest group followed by Whites² (26 %), Asians (15 %) and African Americans³ (9 %).

Los Angeles County reported its first COVID-19 case in late January 2020 and first COVID-19 death on March 11, 2020. As of July 27, 2022, there were more than three million confirmed cases and 32,691 COVID-related deaths in the County (Department of Public Health – Los Angeles, 2022). COVID cases revealed large disparities across race/ethnicity and income. Hispanics accounted for 58.1 % and Whites accounted for 12.2 % of COVID cases. More than 75 % of COVID-19 cases were from the poorest neighborhoods (Los Angeles County, 2022).

3.2. Data

3.2.1. Mobility metrics

We assembled a longitudinal dataset of daily mobility measures from January 1, 2020, to April 16, 2021 (469 days), for residents of Los Angeles County from SafeGraph, a data company that aggregates anonymized location data from mobile phone applications (SafeGraph, 2021). SafeGraph made the data available for COVID related research, but reduced availability after April 16, 2021. Therefore our time period is limited to that date. Availability of the data led to many studies COVID-19 pandemic (Gao et al., 2020; Huang et al., 2020; Jay et al., 2020; Kar et al., 2021; Weill et al., 2020). SafeGraph aggregates data using a panel of GPS points from anonymous mobile devices and determines the home location as the common nighttime location of each mobile device over six weeks to a Geohash-7 granularity (~153 m × ~153 m). All mobility data are anonymized and aggregated to the census block group (CBG) level.⁴ There are 6150 CBGs in the urbanized portion of the county, which accounts for 99 % of the population. Using origin and destination information, the SafeGraph data allow us to construct high-frequency mobility measures among individuals.

The SafeGraph data has more than 850,000 devices for the county, roughly equivalent to an 8.5 % sample. The average number of devices is 135 per CBG, but the distribution is not even. There is a <4 % sample in 176 CBGs (representing 2.8 % of county population), and 204 CBGs have a sample of more than 20 % (representing 3.1 % of the county population). There is no direct way to test the representativeness of the SafeGraph data. We compared overall trends with the Apple Mobility Trends Report and found a high degree of consistency despite the differences in sources.⁵ The Apple data are drawn from Apple product users, while SafeGraph is drawn from both Android and Apple devices. The SafeGraph data has been widely used in COVID-19 studies, and no substantive problems with the data have been identified (Gao et al., 2020; Holtz et al., 2020; Huang et al., 2020; Jay et al., 2020; Kar et al., 2021).

We generate two mobility measures: the average number of CBGs visited each day per device for a given CBG, and the proportion of devices in a given CBG that spent all day at home each day. SafeGraph also provides data on the number of visits to distinct points of interest (POI) each week in every CBG. The visits data is given at the POI level and categorized to a specific location category (e.g., restaurant, grocery store, park). The POI data makes it possible to classify trips by purpose, which then allows us to examine mobility patterns by trip purpose. We developed trip categories based on definitions of the U.S. Department of Transportation Federal Highway Administration (2019). FHWA assigns trip purpose in five categories based on 2017 National Household Travel Survey data. SafeGraph is aggregate data and there is no information on each respondent’s (cellphone) activity. To impute a trip purpose, we use the POI’s North American Industry Classification System (NAICS) code, time of day, and duration of stay. Trip categories and their relationship to POI data are presented in Table 1.

3.3. Socio-demographic characteristics

CBG level income and ethnicity data were obtained from American Community Survey (ACS) data (2014-2018, 5-year pooled). It is well known that travel behavior is related to demographic and socioeconomic characteristics (e.g., Giuliano and Hansen, 2017). We therefore segment CBGs into groups by household income levels and share of minority populations to test for differences across these attributes. We follow the method proposed by Turner and Rawlings (2009) to classify CBGs according to their ethnic composition. If a CBG has more than 50 % minority residents (i.e., non-White), it is categorized as a majority minority neighborhood. If not, it is categorized as non-Hispanic White. If one specific minority accounts for more than 60 % of the population, the CBG is categorized as specific minority dominant. The minority dominant categories are Hispanic (of all races), African American, and other (e.g., Asian, Native American). It is worth noting that more than 90 % of

| Table 1 | Categories of POI visit purpose. |
|---------|----------------------------------|
| Category | Trip Purpose Categories | POI type |
| Shopping | Buy goods (e.g., groceries, clothes, appliances, or gas). | NAICS sector 44-45 (Retail Trade); |
| Family/personal business | Volunteer activities (not paid). | NAICS sector 51 (Information); |
| Social/recreational | Drop off/pick up someone. Attend adult care. Buy services (e.g., dry cleaners, service a car, or pet care). Other general errands (e.g., post office or library). Perform recreational activities (e.g., visit parks, movies, bars, or museums). Exercise (e.g., go for a jog, walk the dog, or go to the gym). Buy meals (e.g., go out for a meal, snack, or carry-out). | NAICS sector 52 (Finance and Insurance); NAICS sector 54 (Professional, Scientific, and Technical Services); NAICS sector 81 (Other Services [except Public Administration]); NAICS sector 92 (Public Administration). |
| Medical/dental | Make a health care visit (e.g., medical, dental, or therapy). | NAICS sector 62 (Health Care and Social Assistance). |
| Work | Trips undertaken for work or business purposes. | NAICS sector 11 (Agriculture, Forestry, Fishing and Hunting); NAICS sector 21 (Mining, Quarrying, and Oil and Gas Extraction); NAICS sector 22 (Utilities); NAICS sector 23 (Construction); NAICS sector 31–33 (Manufacturing); NAICS sector 46–49 (Transportation and Warehousing); NAICS sector 56 (Administrative and Support and Waste Management and Remediation Services); NAICS sector 42 (Wholesale Trade). |

¹ “Hispanic” is defined as Hispanic or Latino of any race.
² “White” is defined as non-Hispanic or Latino White alone.
³ “African Americans” is defined as non-Hispanic or Latino Black alone.
⁴ Users of mobile devices have given permission for their location to be tracked by a variety of mobile apps. The SafeGraph traces a device user’s GPS trajectory from the apps.
⁵ https://covid19.apple.com/mobility.
the other neighborhoods are Asian dominant neighborhoods.

We use three categories for household income. The categories are based on household income quartiles for Los Angeles County (Census Bureau, 2021). Low income is the lowest quartile (< $46,429), medium is the second and third quartiles, and high income is the highest quartile (> $92,358). The intersection of ethnicity and income categories generates twelve population groups. See Table 2 and Fig. 1. The county’s large Hispanic population is evident; 3054 CBGs are Hispanic. Lower-income Hispanic CBGs are concentrated in the central area, and higher-income Hispanic CBGs extend east to the county border. Other concentrations are located in the San Fernando Valley and to the far north in Lancaster/Palmdale. There are few CBGs with predominantly African American populations. The large areas of mixed minorities are generally Asian and Hispanic or Hispanic and African American.

3.4. Other variables

Travel on any given day may be affected by the day of the week and weather. Weekday patterns are different from weekends, and discretionary travel is less frequent during inclement weather. We include weekday and holiday binary variables to account for daily variation. Daily average precipitation and daily maximum temperature data were accessed from the Global Historical Climatology Network (GHCN) (Global Historical Climatology Network, 2021). The meteorological parameters were then interpolated to each CBG using the inverse distance weighting (IDW) method.

Finally, we want to know if travel behavior is affected by intensity of the pandemic. We might expect that as the case rates increase, travel would decline as people avoid the increased risk of exposure. The pandemic severity level was measured through COVID-19 infections data provided by the Los Angeles Times (Los Angeles Times, 2021). The data are collected from California’s Department of Public Health and local public health departments. Cumulative COVID-19 cases and mortality data for Los Angeles County are provided at the neighborhood level within the City of Los Angeles and at city level outside the City of Los Angeles. Table 3 gives descriptive statistics for income and race/ethnicity for our 12 population groups. It can be seen that for low- and middle-income groups, spatial segmentation is greatest for Hispanic and African American groups.

3.5. Methods

There were distinct periods during the pandemic, mainly defined by policy actions. We use these periods to compare mobility patterns under different conditions over the course of the pandemic. We define a total of 5 stages:

- Stage 0 before COVID: 1/1/20 to 3/18/20.
- Stage 1 stay at home: 3/19/20 to 5/7/20. California issues statewide shelter in place order on 3/19; residents to stay at home except for essential activities, non-essential businesses closed, public school shift to online.
- Stage 2 re-opening: 5/6/20 to 6/30/20: Los Angeles County allows selected businesses to reopen with restrictions (e.g., mask mandate, limits on indoor space occupation), some public schools reopen in person or hybrid; Los Angeles Unified School District (LAUSD) online.
- Stage 3 business restrictions: 7/1/20 to 12/13/20, California re-imposes business restrictions in response to COVID resurgence, non-essential business (e.g., indoor restaurants, movie theaters) closed again; LAUSD remains online.
- Stage 4 vaccinations: 12/14/20 – 4/16/21, vaccines become available, first to health care workers, then elderly and those with health problems (January 19, 2021), then all adults; non-essential business remains closed; LAUSD remains online.

We use difference-in-difference (DID) regression to estimate the impact of the various COVID policy stages across our population groups:

\[ Y_{bd} = \alpha + \gamma \cdot \text{stage}_d + \sum_{s \in S} \beta_s \cdot \text{race/ethnicity}_s + \rho \cdot \text{COVID}_d + \phi \cdot \text{Weekday}_d + \lambda_b + \lambda_d + \epsilon_{bd} \]

where:

- \( Y_{bd} \) = mobility measure at CBG \( b \) on day \( d \).
- \( \text{stage}_d \) = the treatment variable, which takes value one for each respective stage.
- \( s \in S \) = race/ethnicity/income category \( s \) in the set of \( S \) categories.
- \( T_{bs} = 1 \) if CBG \( b \) is in group \( s \).
- \( V \) = vector of control variables: COVID case rate, precipitation, maximum temperature.
- \( \text{Holiday}_d = 1 \) if day \( d \) is a holiday.
- \( \text{City}_d = 1 \) if cities of Pasadena and Long Beach.
- \( \text{Weekday}_d = 1 \) for day of week.
- \( \epsilon_{bd} \) = standard errors.

We use the natural logarithm form for the dependent variables due to their distribution. We use low-income White as the reference group for the race/ethnicity/income categories. The coefficients of interest are the interaction terms \( \text{policy}_d \cdot T_{bs} \) to examine the differential effect of the various policy stages. Dummy variables are created for City of Pasadena and Long Beach as these cities have their own department of public health and thus may have different health care resources, stringency of shelter-in-place order enforcement, and other factors that could affect travel behavior.

For DID regression, the parallel trend assumption must be met between the treatment group and the control groups to control for the influence of time-variant factors. It is hard to test the parallel trend assumption in the post-treatment period. Thus, we plot the daily average mobility measures and weekly average POI visits by group and stage to compare the pre-treated trends between the treatment group and the control groups. We find that the pre-treated trends between groups are generally parallel in all stages. Trends are further discussed in the next section.

4. Results

4.1. General mobility change by population group

4.1.1. Descriptive results

As noted above, we use two measures of mobility to estimate general mobility change by population groups: the average number of CBGs visited each day per device, and the proportion of mobile phone users that spent the entire day at home. Tables 4 and 5 give descriptive results for each measure, respectively. The first three columns give the mean values and the last three columns give the difference between the previous stage. All differences are statistically significant at \( p < 0.001 \). It can be seen that the two measures of mobility are quite consistent; CBGs visited drops the most during Stage 1 and the gradually increases. The
average share of devices remaining at home increases the most during Stage 1 and then gradually decreases. 

Tables 4 and 5 show that the average number of CBGs visited before the pandemic is consistent with the literature. In general people in high income neighborhoods travel the most and people in low-income neighborhoods travel the least. Within each income category, people in Hispanic neighborhoods travel the most and those in African American neighborhoods travel the least. In Stage 1 there is a large drop in travel across all income groups, but the drop is greatest for the high-income neighborhoods. There are differences within income categories. Among high income neighborhoods the drop is greatest for white neighborhoods. Hispanic CBGs reduce travel the least in every income category. While there is a clear trend of increasing mobility for all groups through Stages 2 and 3, Hispanic neighborhoods have the highest rates of mobility within each income category. Low-income African American neighborhoods have the lowest mobility in Stage 0 and remain at the bottom of the trend throughout the period. The general mobility stays quite stable between Stages 3 and 4. Interestingly, we see the same pattern for the middle-income neighborhoods for CBGs visited, but there is less variation across race/ethnic groups for staying at home. The figures suggest that people living in Hispanic neighborhoods systematically travel more during the pandemic. These comparisons suggest that people who live in higher income neighborhoods were more likely to adhere to the shelter-in-place order than those from lower income neighborhoods. Higher income neighborhoods also responded more positively to the business re-opening policy. These observations suggest that both income and race/ethnicity matter. The averages given in Tables 4 and 5 do not reveal day to day average share of devices remaining at home increases the most during Stage 1 and then gradually decreases. 

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**Table 3**

Descriptive statistics by population group.

| Population group | Median Income ($) | % White | % Hispanic | % African American | % Other |
|------------------|-------------------|--------|------------|--------------------|--------|
| Low-income White | 35,522            | 64.9%  | 20.6%      | 4.9%               | 9.6%   |
| Low-income Hispanic | 36,376        | 7.4%   | 79.0%      | 7.8%               | 5.8%   |
| Low-income African American | 31,517  | 7.8%   | 21.6%      | 67.9%              | 2.7%   |
| Low-income Other | 34,380            | 10.9%  | 38.2%      | 22.4%              | 28.5%  |
| Middle-income White | 73,203        | 66.8%  | 18.2%      | 4.3%               | 10.8%  |
| Middle-income Hispanic | 64,158       | 14.4%  | 71.9%      | 5.0%               | 8.8%   |
| Middle-income African American | 67,165  | 8.4%   | 15.1%      | 72.2%              | 4.4%   |
| Middle-income Other | 68,345         | 20.1%  | 31.7%      | 11.3%              | 36.9%  |
| High-income White | 135,957           | 71.4%  | 13.7%      | 2.6%               | 12.3%  |
| High-income Hispanic | 108,076       | 25.6%  | 59.6%      | 2.7%               | 12.1%  |
| High-income African American | 115,510  | 8.5%   | 10.1%      | 76.9%              | 4.5%   |
| High-income Other | 117,280           | 27.9%  | 21.9%      | 5.8%               | 44.5%  |

7 American Community Survey (ACS) 5-Year Data (2015–2019).

**Table 4**

Change in CBGs visited by social class.

| Population group | Average CBGs visited by device each day | Absolute difference* |
|------------------|----------------------------------------|-----------------------|
|                  | Stage 0 | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Between Stage 0 & Stage 1 | Between Stage 1 & Stage 2 | Between Stage 2 & Stage 3 | Between Stage 3 & Stage 4 |
| Low-income Hispanic | 2.32   | 1.69   | 1.89   | 2.01   | 2.05   | -0.63      | +0.20     | +0.12     | +0.05     |
| Low-income African | 2.17   | 1.57   | 1.71   | 1.81   | 1.77   | -0.60      | +0.14     | +0.10     | -0.04     |
| Low-income White | 2.17   | 1.57   | 1.75   | 1.92   | 1.98   | -0.60      | +0.18     | +0.17     | +0.06     |
| Low-income Other | 2.30   | 1.60   | 1.77   | 1.90   | 1.93   | -0.70      | +0.17     | +0.13     | +0.03     |
| Middle-income Hispanic | 2.39   | 1.70   | 1.92   | 2.03   | 2.07   | -0.69      | +0.22     | +0.11     | +0.04     |
| Middle-income African American | 2.27   | 1.60   | 1.75   | 1.79   | 1.77   | -0.67      | +0.15     | +0.05     | -0.03     |
| Middle-income White | 2.31   | 1.52   | 1.76   | 1.89   | 1.91   | -0.81      | +0.24     | +0.13     | +0.02     |
| Middle-income Other | 2.40   | 1.60   | 1.80   | 1.93   | 1.96   | -0.80      | +0.20     | +0.13     | +0.04     |
| High-income Hispanic | 2.48   | 1.65   | 1.91   | 2.02   | 2.06   | -0.83      | +0.26     | +0.11     | +0.04     |
| High-income African American | 2.31   | 1.54   | 1.73   | 1.78   | 1.73   | -0.77      | +0.19     | +0.05     | -0.05     |
| High-income White | 2.45   | 1.50   | 1.80   | 1.93   | 1.94   | -0.95      | +0.30     | +0.13     | +0.01     |
| High-income Other | 2.47   | 1.55   | 1.79   | 1.91   | 1.94   | -0.93      | +0.24     | +0.12     | +0.03     |

*All within group differences are significant at p < 0.001.
Table 5
Change in proportion of mobile phone users spending entire day at home.

| Population group          | Average proportion of completely stay at home device | Absolute difference* |
|---------------------------|-----------------------------------------------------|-----------------------|
|                           | Stage 0    | Stage 1    | Stage 2    | Stage 3    | Stage 4    | Between Stage 0 & Stage 1 | Between Stage 1 & Stage 2 | Between Stage 2 & Stage 3 | Between Stage 3 & Stage 4 |
| Low-income Hispanic       | 28 %       | 44 %       | 39 %       | 34 %       | 34 %       | +16 %                  | -5%                     | -4%                      | -1%                      |
| Low-income African American| 32 %       | 45 %       | 42 %       | 37 %       | 36 %       | +13 %                  | -3%                     | -5%                      | -1%                      |
| Low-income White          | 30 %       | 46 %       | 42 %       | 35 %       | 34 %       | +16 %                  | -4%                     | -7%                      | -2%                      |
| Low-income Other          | 27 %       | 45 %       | 42 %       | 37 %       | 36 %       | +18 %                  | -3%                     | -5%                      | -1%                      |
| Middle-income Hispanic    | 25 %       | 44 %       | 38 %       | 34 %       | 33 %       | +19 %                  | -6%                     | -4%                      | -1%                      |
| Middle-income African American | 28 %     | 45 %       | 40 %       | 37 %       | 37 %       | +17 %                  | -5%                     | -3%                      | -1%                      |
| Middle-income White       | 24 %       | 47 %       | 39 %       | 34 %       | 33 %       | +23 %                  | -8%                     | -6%                      | -1%                      |
| Middle-income Other       | 25 %       | 48 %       | 42 %       | 37 %       | 36 %       | +23 %                  | -6%                     | -5%                      | -1%                      |
| High-income Hispanic      | 23 %       | 45 %       | 37 %       | 33 %       | 32 %       | +22 %                  | -8%                     | -4%                      | -1%                      |
| High-income African American | 25 %     | 47 %       | 42 %       | 38 %       | 38 %       | +22 %                  | -5%                     | -4%                      | 0%                       |
| High-income White         | 20 %       | 47 %       | 38 %       | 32 %       | 32 %       | +27 %                  | -9%                     | -6%                      | 0%                       |
| High-income Other         | 22 %       | 50 %       | 42 %       | 37 %       | 36 %       | +28 %                  | -8%                     | -5%                      | -1%                      |

*All within group differences are significant at p < 0.001.

Fig. 2. Mobility change by time: a. CBGs visited per device per day by income group; b. Proportion of devices that stayed at home all day.
variation within each stage. Fig. 2 shows daily mobility trends by income level. Fig. 2a shows the average number of CBGs visited per device per day, and Fig. 2b shows the share of devices staying at home each day. The color blocks in the figures denote stages. The pattern in Stage 0 is consistent with known travel patterns: high income CBGs have more travel; low income CBGs have the least travel. Fig. 2a and b are quite consistent. Both show that reduced mobility began shortly before the appearance of vaccines generates another surge in mobility, but activity levels do not reach pre-pandemic levels.

4.2. Difference-in-difference model

We use the DID analysis to test for effects of stage, income and race/ethnicity. Tables 6 and 7 present results for the CBGs visits and stay-at-home variables, respectively. The baseline group is low-income white neighborhoods. The columns give results for each stage. We begin with some general observations. First, variable coefficients are highly significant; this is due to the large sample size. We therefore focus more on direction and magnitude than significance. Second, the explanatory level of the models declines with each stage. The random variability of travel appears to increase with the recovery of travel.

We turn now to variable coefficients. For visits, the stage coefficient is strongly negative, then turns positive and increases in each stage. For stay at home, the stage coefficient is strongly positive, then turns negative and becomes increasingly negative. The models give consistent results and suggest that after the first stay at home order COVID health policies had little impact on behavior. Some possible explanations are: 1) less public confidence in public policies that seemed to change arbitrarily, 2) deferring some types of travel (e.g. medical care) became more difficult as the pandemic continued; 3) fatigue or stress of staying at home that intensified over time.

### Table 6

| (1) Log | (2) Log | (3) Log | (4) Log |
|--------|--------|--------|--------|
| CBGs   | CBGs   | CBGs   | CBGs   |
| Visited| Visited| Visited| Visited|
| Stage 1: Shelter-in-Place Order | Stage 2: | Stage 3: | Stage 4: |
| Reopen | Business | Business | Vaccination |
| Post-policymaker | Post | Post | Post |
| Post × Low-income White | Hispanic | Post × Low-income African American | Post × Low-income Other | Post × Middle-income White | Post × Middle-income Hispanic | Post × Middle-income African American | Post × High-income Other | Post × High-income White | Post × High-income Hispanic | Post × High-income African American | Post × High-income Other | New confirmed COVID case growth rate | Precipitation | Max temperature | Holiday | Pasadena dummy | Long Beach dummy | Day of week dummy | Neighborhood fixed effect | Time fixed effect |
| Ref. | 0.057*** | 0.011** | 0.007* | -0.048*** | 0.039*** | 0.017*** | -0.011*** | -0.082*** | -0.013*** | 0.017*** | -0.027*** | -0.061*** | -0.018*** | 0.018*** | 0.004*** | -0.068*** | -0.104*** | -0.135*** | Yes | Yes | Yes | Yes |
| Ref. | 0.021*** | 0.012*** | -0.057*** | -0.013*** | 0.018*** | 0.026*** | -0.031*** | -0.014*** | 0.044*** | 0.015*** | 0.065*** | 0.030*** | 0.001** | 0.001*** | 0.000 0.001*** | 0.001*** | -0.057*** | 0.019*** | Yes | Yes | Yes | Yes |
| Ref. | 0.012*** | 0.009*** | -0.064*** | -0.012*** | -0.155*** | 0.006*** | 0.065*** | 0.001 | -0.001 | 0.016*** | 0.019*** | 0.065*** | 0.000 | 0.028*** | 0.013*** | 0.000 | -0.026*** | 0.019*** | Yes | Yes | Yes | Yes |
| Ref. | 0.012*** | 0.009*** | -0.100*** | -0.023*** | -0.028** | 0.002 | 0.086** | 0.007 | 0.023*** | 0.019*** | 0.005 | 0.012*** | 0.005 | 0.028*** | 0.004*** | 0.115 | 0.115 | 0.022 | Yes | Yes | Yes | Yes |
| Ref. | 0.012*** | 0.009*** | -0.100*** | -0.023*** | -0.028** | 0.002 | 0.086** | 0.007 | 0.023*** | 0.019*** | 0.005 | 0.012*** | 0.005 | 0.028*** | 0.004*** | 0.115 | 0.115 | 0.022 | Yes | Yes | Yes | Yes |

### Table 7

| (1) | (2) | (3) | (4) |
|-----|-----|-----|-----|
| Log(% Stay Home) | Log(% Stay Home) | Log(% Stay Home) | Log(% Stay Home) |
| Post-policy | Post × Low-income White | Post × Low-income Hispanic | Post × Low-income African American |
| Ref. | -0.062*** | -0.070*** | -0.036*** | 0.121*** |
| Ref. | -0.031*** | 0.056*** | 0.015*** | -0.060*** |
| Ref. | 0.008*** | 0.075*** | 0.034*** | -0.019*** |
| Ref. | 0.015*** | 0.074*** | 0.043*** | 0.005 |
| Ref. | 0.021*** | -0.022*** | 0.044*** | -0.022*** |
| Ref. | 0.054*** | 0.045*** | 0.061*** | -0.002 |
| Ref. | 0.001 | 0.028*** | 0.024*** | -0.002 |
| Ref. | 0.000 | 0.028*** | 0.024*** | -0.002 |
| Ref. | 0.011 | 0.028*** | 0.024*** | -0.002 |
| Ref. | 0.028*** | 0.045*** | 0.061*** | -0.002 |
| Ref. | 0.000 | 0.028*** | 0.024*** | -0.002 |
| Ref. | 0.011 | 0.028*** | 0.024*** | -0.002 |
| Ref. | 0.028*** | 0.045*** | 0.061*** | -0.002 |
| Ref. | 0.000 | 0.028*** | 0.024*** | -0.002 |

* p < 0.05, ** p < 0.01, *** p < 0.001.
Income/race/ethnicity coefficients are mostly significant but often of small magnitude. Higher income and whiter minority neighborhoods reduce travel more than lower income and majority minority neighborhoods in stage 1. High-income White neighborhoods increased travel the most in Stage 2, while low-income African American neighborhoods increased travel the least. Results for stage 3 are mixed. Only low-income Hispanic neighborhoods show relatively more travel. Staying at home decreases less for middle- and high-income Whites as well as high income Hispanics. In stage 4 travel increases the most in low-income Hispanic neighborhoods while staying at home decreases the most for high income whites and Hispanics.

With respect to control variables, the new confirmed COVID case rate coefficient for visits is negative and of similar magnitude in stages 1 through 3 and becomes positive in stage 4. For stay at home, the coefficient is positive for stage 1, negative for stages 2 and 3, and not significant for stage 4, suggesting that case rates had little effect on travel. Residents of Pasadena reduced mobility more than other areas in Los Angeles County while residents of Long Beach reduced mobility less, likely reflecting differences in local travel restriction policies.

Our results on income are consistent with prior studies (Atchison et al., 2020; Brough et al., 2021; Clay and Rogus, 2021; Goldman et al., 2021). High-income households engage in more discretionary travel and are more likely to have jobs that can be conducted from home. They therefore have both greater abilities to reduce travel when necessary and increase travel when restrictions are relaxed. In contrast, low-income households engage in less discretionary travel, and are more likely to have jobs that require traveling to the job site (Blau et al., 2020; Garfield et al., 2020). Our results show that race/ethnicity also has significant effects, as for example low-income Hispanic neighborhoods showing the smallest decrease in travel in stage 1.

4.3. Mobility changes by trip purpose

Our results show there was less reduction in travel in low-income minority neighborhoods. Why might this be the case? As discussed in Section 2, low-income and minority workers are more likely to be employed in sectors that are deemed essential and require physical presence. Higher-income workers are more likely to be employed in jobs that can be conducted remotely. Higher-income households also have more capacity to purchase services (e.g. grocery deliveries) to avoid travel (Kar et al., 2021). We use trip purpose to examine whether changes in travel are related to changes in trip purpose.

4.3.1. Descriptive results

We used the POIs to impute trip purpose, as shown in Table 1. The resulting categories are only approximate. For example, spending time at a restaurant could be social/recreational (purchasing a meal) or work. To determine the most likely trip purpose, we compared the POI’s location (CBG), the visitor’s primary daytime location (i.e. where he/she stays for the longest time between 9 AM and 5 PM), and the visitor’s home location. If a visitor’s primary daytime location is at a POI different from his/her home location, we consider the visit a work trip. We generated O-D matrices for each trip purpose by identifying the origins of devices visiting each POI.

Fig. 3 shows average trip frequency per device per week by purpose (rows), income group (columns), and race/ethnic group (color codes). The Y axis for each trip purpose is scaled to frequency. There are several observations to be drawn from Fig. 5: 1) each trip purpose has a different temporal pattern, but all reflect the steep decline at the beginning of Stage 1 and gradual recovery thereafter, even before COVID vaccines became available; 2) non-work travel declines more steeply at the beginning of Stage 1 than work travel; 3) social/recreational and shopping travel increases more than other travel until Stage 3, when many businesses were again closed; 4) all travel purposes rebound in Stage 4; 5) medical-related visits tick up in Stage 3, perhaps because households are no longer able to defer needed medical care.

Fig. 3 also shows that travel varies across income and racial groups. In general, lower-income neighborhoods reduce work travel less relative to pre-pandemic levels, while patterns for other trip purposes are relatively consistent across income groups. Within low-income neighborhoods, Hispanic neighborhoods retain the highest rate of work travel throughout the pandemic stages. The higher rate of work travel is consistent with less ability to work remotely in low wage jobs (Atchison et al., 2020; Blau et al., 2020; Garfield et al., 2020). Low-income Hispanic neighborhoods also show the highest rate of social/recreational and shopping travel; these differences tend to dissipate with income level.

4.3.2. DID model results

We use the same model form and control variables to examine the effects of income and race/ethnicity on the frequency of visits by trip purpose. We present results for work, social/recreational, and shopping in Tables 8–10 respectively. All tables have the same structure as Table 6.

Work trips decline significantly at the beginning of Stage 1. Even when businesses re-open, work trips continue to decline until Stage 3. There are distinct income and race/ethnicity effects; work trips from low-income Hispanic neighborhoods decline less, while work trips from high-income White, high income Other, and middle-income White neighborhoods reduce work trips more. These patterns remain in Stage 2 and reverse in Stages 3 and 4. More people living in high-income neighborhoods reduce their work trips even after business re-opens. The COVID case rate has a depressive effect in Stage 1, but not in the other stages.

Tables 9 and 10 give the DID results for social/recreational and shopping visits, respectively. These visits are more strongly affected by both Stage 1 and Stage 2 than work trips, as expected. For both trip purposes, the average per device/week drops by about one full trip. Stage 2 results in a slight increase, and Stage 3 results in a slight decrease, likely because of business closures. Stage 4 is associated with increases in both trip purposes. For social/recreational visits, low-income Hispanic neighborhoods reduce visits the least, and high-income white neighborhoods reduce visits the most. In the later stages, high-income white neighborhoods increase visits the most and low-income African American neighborhoods increase visits the least. The pattern is similar for shopping, except that middle-income Hispanic neighborhoods reduce shopping visits the least in Stage 1. The COVID case rate control variable has the same effect as in the previous models.

We summarize the trip purpose results as follows. The shelter-in-place order results in travel reductions for all purposes but with different magnitude. Trips for all purposes were found to have the greatest decline in Stage 1 when compared to the following stage (trip reduction rates range from 98 percentage points (shopping trips) to 122 percentage points (social/recreational trips). Stage 2, which re-opened restaurants and bars, has a positive effect on trips for social/recreational and shopping activities (5 percentage points), but not for work trips. Stage 3 resulted in further trip declines for social/recreational and shopping trips (3 percentage points and 2 percentage points), but not for work trips (14 percentage points increase). Stage 4 led to increase in work, social/recreational, and shopping trips (7 percentage points, 5 percentage points and 7 percentage points).

Within these general trends, differences between income and race/ethnic groups show generally less reduction in travel for low-income groups, and greater later stage increases for high-income groups. When controlling for COVID-19 cases and other covariates, Whites tend to reduce more work trips during the shelter-in-place period. In other words, people in ethnic minority neighborhoods, whether high-income or low-income, appear to have less opportunity to work remotely than those in otherwise-similar White neighborhoods. Similarly, low-income

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6 Full results for other trip purposes are available upon request.
Fig. 3. Origin-destination analysis categorized by trip purpose for different population groups.
and middle-income groups reduce work trips less than otherwise-similar high-income groups during the shelter-in-place period. When COVID vaccines became available, residents of White neighborhoods show the largest increase in discretionary trips, while residents of otherwise-similar African American neighborhoods show less increase or even a decrease in trips for the same purpose.

### 5. Conclusions

Our analysis may be summarized as follows. First, our results on travel responses to the various pandemic stages track with traffic observations. The first stay at home order had a strong effect; levels of travel plummeted in the early stage of the pandemic. Travel began to gradually recover before the stay at home order was lifted and continued through the later stages. The second period of restriction (stage 3) slowed or stopped increases for some travel purposes (shopping, social/leisure) but not for others. The availability of vaccines allowed the travel recovery to resume, despite no policy changes for business activities.

Within these general trends, income level and ethnicity explain differences across neighborhoods. High-income groups, notably high-income White neighborhoods, have the strongest response to travel restrictions policy implementation and vaccination availability. In contrast, low-income groups and in particular low-income minority neighborhoods responded less; these groups reduced mobility less in Stage 1 and increased mobility less in Stage 2. More limited response to Stage 1 does not appear to be a matter of compliance. Our trip purpose models support the argument of differences in occupation and associated opportunities for working at home. Evidence suggests that although people perceived increased health risks at their work location, they would not perceive increased health risks at their work location, they would not

### Table 9

Difference-in-differences regression estimates, social and recreational trips.

|                          | (1)          | (2)          | (3)          | (4)          |
|--------------------------|--------------|--------------|--------------|--------------|
| Post-policy              | –1.226***    | 0.049**      | –0.027*      | 0.053***     |
| Post × Low-income White  |              |              |              |              |
| Post × Low-income Hispanic | 0.220***     | 0.025        | 0.095**      | 0.075***     |
| Post × Low-income African American | 0.074**     | –0.181***    | 0.003        | –0.164***    |
| Post × Middle-income Other | 0.055**      | –0.056**     | 0.038        | 0.016        |
| Post × Middle-income White | –0.070***    | 0.067***     | 0.090***     | 0.012        |
| Post × Middle-income Hispanic | 0.159***    | 0.044**      | 0.088***     | 0.065***     |
| Post × Middle-income African American | 0.060**    | –0.033       | 0.042        | –0.085***    |
| Post × Middle-income Other | 0.064***     | 0.053**      | 0.107***     | 0.044***     |
| Post × High-income White             | –0.184***    | 0.132***     | 0.149***     | 0.061***     |
| Post × High-income Hispanic         | 0.035*       | 0.059**      | 0.087***     | 0.083***     |
| Post × High-income African American | –0.049       | 0.016        | 0.034        | –0.132***    |
| Post × High-income Other            | –0.061***    | 0.069***     | 0.081***     | 0.059***     |
| New confirmed COVID case growth rate | –0.269***    | 0.187***     | 0.062***     | 0.007       |
| Precipitation                | –0.263***    | –0.081***    | –0.102***    | –0.097      |
| Max temperature              | 0.012***     | 0.003**      | 0.005***     | 0.005***     |
| Holiday                      | 0.184***     | 0.052***     | 0.037***     | –0.019***    |
| Pasadena dummy               | 0.918***     | 0.709***     | 0.941***     | –0.297      |
| Long Beach                   | 1.006***     | 0.991***     | 1.052***     | –0.466      |
| Day of week dummy            | Yes          | Yes          | Yes          | Yes          |
| Neighborhood fixed effect     | Yes          | Yes          | Yes          | Yes          |
| Time fixed effect Obs.        | 116,586      | 85,745       | 189,812      | 256,773     |
| Adj. R²                      | 0.69         | 0.20         | 0.12         | 0.13         |

*p < 0.05, ** p < 0.01, *** p < 0.001.
least confidence in traveling (Stoler et al., 2021; Willis et al., 2021). and low-income populations have the highest vaccine hesitancy and vaccines across various population groups (Siegel et al., 2021; Wong explained by unequal access to vaccines and different levels of trust in these differences might be explained by unequal access to vaccines and different levels of trust in vaccines across various population groups (Siegel et al., 2021; Wong et al., 2022). Compared to other population groups, African American and low-income populations have the highest vaccine hesitancy and least confidence in traveling (Stoler et al., 2021; Willis et al., 2021).

Overall, our findings provide evidence of social injustice during the COVID-19 pandemic. The same populations—low income, predominantly minority—disadvantaged in other circumstances (e.g., financial and medical resources) are also disadvantaged in the COVID-19 pandemic. These populations have fewer options to avoid exposure and risk and are suffering the highest rates of both health and economic impacts (Ahmad et al., 2020; Brough et al., 2021; Jacobs, 2011). Given the prevalence of comorbidity factors and poor health insurance coverage among low-income and ethnic minority dominant communities, the risks of less physical distancing and lack of access to vaccines are substantial. These communities are also more likely to lack sufficient testing, vaccination, and contact tracing capacity to monitor and thwart COVID-19 outbreaks (Cardona et al., 2021; Maroko et al., 2020; Schmidt et al., 2021; Thakore et al., 2021).

Our findings suggest the need for more responsive public policy to protect marginalized populations from the effects of COVID. Now well into the third year of the pandemic, low income, minority populations continue to be disproportionately represented in the COVID hospitalization and death statistics. Policy strategies include more education and vaccine access as well as broad distribution of testing kits in high vulnerability neighborhoods; more social distancing, frequent hand-washing, and extensive cleaning at the worksite; more flexible work arrangements; and greater availability of paid sick leave. Finally, financial mechanisms to facilitate online purchases and home deliveries should be considered.

There are some limitations to our work. First, our data include only Los Angeles County. Given that the response to the pandemic has largely been left to states and counties, every county is to some extent a unique case. The question is how much this affects the generalizability of results. We would argue that results are generalizable to the extent that socioeconomic conditions hold in other places. High-income, highly educated workers are more likely to be able to work at home, whether in Los Angeles or any other metropolitan area. Minorities make up a large portion of service industry jobs across the US. Low-income households travel less due to income constraints. We therefore expect future studies of other states or metro areas to be broadly consistent.

Second, we followed Turner and Rawlings (2009)’s method to categorize ethnic neighborhoods and used income quartiles to distinguish relative income levels, which allows for large enough groups for both high- and low-income race/ethnicity categories. However, there are various methods to define minority and low-income neighborhoods and there is no “gold standard” for these measures. Different ethnic and income category definitions might lead to different results. Sensitivity analysis could be applied in further research to examine the effect of different ethnic and income category definitions on mobility changes.

Third, the global pandemic continues to evolve as this paper is written. We know from studies of earthquakes and other disasters that people can make dramatic changes in travel behavior for a short period of time but then quickly revert to regular behavior. Anecdotal evidence suggests that people have become increasingly resistant to behavior changes that have economic or other costs. As the pandemic wears on, more people likely have become fatigued with staying at home, while others may have found it increasingly difficult to defer activities requiring travel.

COVID-19 presents a unique opportunity to explore how people react and respond to a long-term crisis. Unlike floods or earthquakes, the pandemic is global and the timeframe for defeating the virus is uncertain. The duration of the pandemic has gone on far longer than temporary adjustments can be sustained; the question is, how much of the adjustments made will continue beyond the pandemic. Working from home and online shopping are of particular interest in this context. COVID-19 also illustrates how social injustice feeds on itself. The most vulnerable neighborhoods are the places where people have the least options for avoiding travel and hence the greatest risk of exposure. COVID-19 is one more illustration of social disparities that need to be addressed.

**Table 10**

Difference-in-differences regression estimates, shopping trips.

|                      | (1)   | (2)   | (3)   | (4)   |
|----------------------|-------|-------|-------|-------|
| Place Order          | Ref.  | Ref.  | Ref.  | Ref.  |
| Post-policy          | 0.001 | 0.001 | 0.001 | 0.001 |
| Post × Low-income White Hispanic | 0.025 | 0.025 | 0.025 | 0.025 |
| Post × Low-income African American | 0.031 | 0.031 | 0.031 | 0.031 |
| Post × Low-income Other Hispanic | 0.008 | 0.008 | 0.008 | 0.008 |
| Post × Middle-income White Hispanic | 0.106 | 0.106 | 0.106 | 0.106 |
| Post × Middle-income African American | 0.037 | 0.037 | 0.037 | 0.037 |
| Post × High-income White | 0.097 | 0.097 | 0.097 | 0.097 |
| Post × High-income Hispanic | 0.095 | 0.095 | 0.095 | 0.095 |
| Post × High-income Other Hispanic | 0.036 | 0.036 | 0.036 | 0.036 |
| Post × High-income African American | 0.017 | 0.017 | 0.017 | 0.017 |
| New confirmed COVID case growth rate | -0.125*** | -0.125*** | -0.125*** | -0.125*** |
| Precipitation | -0.001*** | -0.001*** | -0.001*** | -0.001*** |
| Max temperature | 0.010*** | 0.010*** | 0.010*** | 0.010*** |
| Holiday | 0.225*** | 0.225*** | 0.225*** | 0.225*** |
| Pasadena dummy | 0.247 | 0.247 | 0.247 | 0.247 |
| Long Beach dummy | -0.325 | -0.325 | -0.325 | -0.325 |
| Day of week dummy | Yes | Yes | Yes | Yes |
| Neighborhood fixed effect | Yes | Yes | Yes | Yes |
| Time fixed effect | Yes | Yes | Yes | Yes |
| Obs. | 116,604 | 85,785 | 189,752 | 256,603 |
| Adj. R² | 0.64 | 0.33 | 0.29 | 0.26 |

* p < 0.05, ** p < 0.01, *** p < 0.001.
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.

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References
Ahmad, K., Erzouq, S., Shah, N., Nazir, U., Morrison, A.R., Choudhary, G., Wu, W.C., 2020. Association of poor housing conditions with COVID-19 incidence and mortality across US counties. PLoS One 15, 1–13. https://doi.org/10.1371/journal.pone.0231227.
Atchison, C., Bowan, L., Vrinden, C., Redd, R., Pristera, P., Eaton, J., Ward, H., 2020. Perceptions and behavioural responses of the general public during the COVID-19 pandemic: A cross-sectional survey of UK Adults 1–21. 10.1101/2020.04.01.20050039.
Barrett-bowzell, Z., Mobarak, A.M., 2020. The Benefits and Costs of Social Distancing in Rich and Poor Countries 1–14.
Blau, F.D., Koehofer, J., Meyerhofer, P., 2020. Who are the essential and frontline workers? SSRN Electron. J. https://doi.org/10.2139/ssrn.3664432.
Bogart, L.M., Ojikutu, B.O., Tyagi, K., Klein, D.J., Mutchler, M.G., Dong, L., Lawrence, S., Brough, R., Freedman, M., Phillips, D.C., 2021. Understanding socioeconomic disparities in travel behavior during the COVID-19 pandemic. J. Region. Sci. 61 (4), 753–774.
Cardona, S., Felipe, N., Fischer, K., Sebgl, N.J., Schwartz, B.E., 2021. Vaccination rates in California. All errors and omissions are the responsibility of the authors.

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References
Ahmad, K., Erzouq, S., Shah, N., Nazir, U., Morrison, A.R., Choudhary, G., Wu, W.C., 2020. Association of poor housing conditions with COVID-19 incidence and mortality across US counties. PLoS One 15, 1–13. https://doi.org/10.1371/journal.pone.0231227.
Atchison, C., Bowan, L., Vrinden, C., Redd, R., Pristera, P., Eaton, J., Ward, H., 2020. Perceptions and behavioural responses of the general public during the COVID-19 pandemic: A cross-sectional survey of UK Adults 1–21. 10.1101/2020.04.01.20050039.
Barrett-bowzell, Z., Mobarak, A.M., 2020. The Benefits and Costs of Social Distancing in Rich and Poor Countries 1–14.
Blau, F.D., Koehofer, J., Meyerhofer, P., 2020. Who are the essential and frontline workers? SSRN Electron. J. https://doi.org/10.2139/ssrn.3664432.
Bogart, L.M., Ojikutu, B.O., Tyagi, K., Klein, D.J., Mutchler, M.G., Dong, L., Lawrence, S., Brough, R., Freedman, M., Phillips, D.C., 2021. Understanding socioeconomic disparities in travel behavior during the COVID-19 pandemic. J. Region. Sci. 61 (4), 753–774.
Cardona, S., Felipe, N., Fischer, K., Sebgl, N.J., Schwartz, B.E., 2021. Vaccination rates in California. All errors and omissions are the responsibility of the authors.

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The authors are grateful to SafeGraph for providing mobile device data. Comments from anonymous reviewers helped to improve the analysis and paper organization. This research was supported by the METRANS Transportation Consortium at University of Southern California. All errors and omissions are the responsibility of the authors.
ABC News. 2020. Timeline: How coronavirus got started. available at: https://abcnews.go.com/Health/timeline-coronavirus-started/story?id=69435165 (accessed on 23 December 2021).

Norris, P., 2001. Digital divide: Civic engagement, information poverty, and the Internet worldwide.

Painter, M., Qiu, T., 2020. Political beliefs affect compliance with COVID-19 social distancing orders. SSRN Electron. J. https://doi.org/10.2139/ssrn.3569998.

Quinn, S.C., Lama, Y., Jamison, A., Freimuth, V., Shah, V., 2021. Willingness of black and white adults to accept vaccines in development: an exploratory study using national survey data. Am. J. Heal. Promot. 35, 571–579. https://doi.org/10.1177/0890117120979918.

SafeGraph. 2021. Social Distancing Metrics. available at: https://docs.safegraph.com/docs/social-distancing-metrics (accessed on 23 December 2021).

Schmidt, H., Weintraub, R., Williams, M.A., Miller, K., Buttenheim, A., Sadecki, E., Wu, H., Deipholde, A., Nagad, N., Gontin, LO., Shen, AA., 2021. Equitable allocation of COVID-19 vaccines in the United States. Nat. Med. 27, 1298–1307. https://doi.org/10.1038/s41591-021-01379-6.

Siegel, M., Jain, J.C., Boykin, M., Owens, A., Maratore, R., Nunn, T., Oh, J., 2021. Racial/ethnic disparities in state-level COVID-19 vaccination rates and their association with structural racism. J. Racial Ethn. Heal. Disparities. https://doi.org/10.1007/s40615-021-01173-7.

Stoler, J., Enders, A.M., Klofstad, C.A., Uscinski, J.E., 2021. The limits of medical trust in mitigating COVID-19 vaccine hesitancy among Black Americans. J. Gen. Intern. Med. 36, 3629–3631.

Thakore, N., Khazanchi, R., Orav, E.J., Ganguli, J., 2021. Association of Social Vulnerability, COVID-19 vaccine site density, and vaccination rates in the United States. Healthcare 9, 100583. https://doi.org/10.1016/j.hjdsi.2021.100583.

Torrats-espinoza, G., 2021. Using machine learning to estimate the effect of racial segregation on COVID-19 mortality in the United States. 10.1073/pnas.2015577118/DCSupplemental.y.