The role of the California tier system in controlling population mobility during the COVID- 19 pandemic

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Abstract

Background

Policies to restrict population mobility are a commonly used strategy to limit the transmission of contagious diseases. Among measures implemented during the COVID-19 pandemic were dynamic stay-at-home orders informed by real-time, regional-level data. California was the only state in the U.S. to implement this novel approach; however, the effectiveness of California's four-tier system on population mobility has not been quantified.

Methods

Utilizing data from mobile devices and county-level demographic data, we evaluated the impact of policy changes on population mobility and explored whether demographic characteristics explained variability in responsiveness to policy changes. For each California county, we calculated the proportion of people staying home and the average number of daily trips taken per 100 persons, across different trip distances and compared this to pre-COVID-19 levels.

Results

We found that overall mobility decreased when counties moved to a more restrictive tier and increased when moving to a less restrictive tier, as the policy intended. When placed in a more restrictive tier, the greatest decrease in mobility was observed for shorter and medium-range trips, while there was an unexpected increase in the longer trips. The mobility response varied by geographic region, as well as county-level median income, gross domestic product, economic, social, and educational contexts, the prevalence of farms, and recent election results.

Conclusions

This analysis provides evidence of the effectiveness of the tier-based system in decreasing overall population mobility to ultimately reduce COVID-19 transmission. Results demonstrate that socio-political demographic indicators drive important variability in such patterns across counties.

Introduction

Population mobility is a critical consideration when examining the spread of infectious diseases from a public health perspective. Mobility, or the distances that people cover on a daily basis and the frequency of their trips, is an indication of their potential exposure to infected individuals (for communicable diseases) (1). When officials are attempting to contain an infectious agent like the SARS-CoV-2 virus in a population, non-pharmaceutical interventions like government orders that restrict human mobility are

commonly put in place to minimize exposure and viral spread. In the context of COVID-19, local and federal governments around the world applied various measures to limit the transmission of the virus by reducing population mobility. However, the unprecedented nature of this global pandemic made guidance challenging to establish, partly due to a lack of clear evidence of the effectiveness of various measures.

A range of policies were implemented at various levels of government, including the use of face masks, physical distancing, limiting the capacity of indoor spaces, closing non-essential businesses and spaces, improving indoor ventilation, cleaning and disinfecting surfaces, and monitoring individual health through temperature-taking and COVID-19 testing (2–5). Along with encouraging these policies, many governments also implemented stay-at-home orders to minimize the spread of infection. To various degrees, these orders required residents to stay at home, with exceptions for necessary or critical tasks (6). Compared to regions where stay-at-home orders were not implemented, areas with stay-at-home orders had a reduction in the number of COVID-19 cases and deaths as shown as early as five days after implementation, thus minimizing viral spread (7, 8). While the main mechanism that may contribute to such a reduction in COVID-19 is likely driven by changes in mobility patterns, there is little evidence to demonstrate the effect of these measures on mobility.

Several previous studies have focused on the effects of mobility restriction policies on COVID-19 transmission rates and have largely identified that mobility restrictions led to reductions in COVID-19 transmission (5, 9, 18, 19, 10–17). Fewer studies, however, have assessed the impacts of population mobility from COVID-19 policies. We identified 20 papers that have investigated this relationship, which are provided in Table S1. Seven of these studies assessed the impact of these policies on mobility within the United States (U.S.) only (20–24), while thirteen have explored this relationship in other parts of the world including China, Canada, Poland, Italy, France, Hungary, Greece, and on a global scale (5, 12, 33–37, 25–32). Certain countries, including China, the United Kingdom, South Africa, and Israel, utilized regional-level, real-time evidence to implement various levels of mobility restriction to reduce the spread of COVID-19 (38–40). These studies concluded that the analyzed policies reduced mobility and highlighted their overall effectiveness in decreasing COVID-19 transmission.

On August 30th, 2020, California introduced the Blueprint for a Safer Economy, a comprehensive, county-by-county tier-system to control virus spread through policy restrictions, based on county-specific COVID-19 test positivity and case rates (41). This tier system was put forth by California Governor Gavin Newsom as an evidence-based approach to combat the COVID-19 pandemic, considering local indicators of viral transmission. California was the first and only state in the U.S. to implement such a policy, which differed from state-wide stay-at-home orders due to its county-level criteria for determining policy restrictions. The California system included four tiers, with tier one being the most restrictive (purple) and tier four (yellow) being the least. As this system was color-coded, it allowed for a clear and accessible indicator of COVID-19 risks for people and businesses in California. The tier of each county was evaluated based on epidemiological evidence of COVID-19 risks. On October 6th, 2020, California implemented an additional health equity metric that required counties to make tangible efforts to eliminate disparities by improving COVID-19 positivity rates in the most disadvantaged communities

before moving to a less restrictive tier (42). Once California began administering vaccines, the tier system shifted to adjust for vaccines being administered.

Restrictions for businesses in each county corresponded to the tier for which they were classified; for instance, at Tier 1, non-essential indoor businesses were closed, and essential indoor businesses were reduced to a maximum capacity of 25%, while at Tier 4, most indoor businesses were open with some modifications. To our knowledge, the impacts of this tier system on population mobility have not been evaluated. Furthermore, the role of different socio-political and demographic indicators may provide insight as to why mobility patterns vary from county to county. In counties that have a higher proportion of essential workforce, such as farmworkers for example, people may not have the privilege to work from home and therefore the mobility levels may not change with lockdowns, while counties with fewer essential workers may have more choice in restricting their mobility. Previous studies have also identified that certain sociodemographic characteristics, such as race and ethnicity, may predispose populations to disproportional COVID-19 exposure risk and impact, and these differences may in part explain differences in the relationship between policy implementation and mobility changes within and between counties (43, 44). Understanding spatial differences in the effectiveness of policies aimed to reduce population mobility and what drives these variations can be important to tailor actions based on county-level demographics and populations. Considering the response of populations at the county level can be used to promote equitable policies that account for disparities in exposure risk and associated protective measures. Additionally, evaluating the effects of these measures on shorter and longer distance travel can be helpful to further understand how populations change their travel behaviors in response to these policies.

This paper aims to evaluate the effect that the Blueprint for a Safer Economy, referred to subsequently as the California tier system, had on population mobility during the COVID-19 pandemic during its implementation from August 31st, 2020, to June 15th, 2021. Secondly, this study aims to understand if demographic characteristics at the county level explain differences in how California counties' mobility patterns changed in response to changing restrictions during policy implementation.

Methods

Data sources

Daily travel data at the county level was downloaded from the U.S. Bureau of Transportation Statistics (45). This travel information is estimated by the Maryland Transportation Institute and Center for Advanced Transportation Technology Laboratory at the University of Maryland using mobile device data. This includes data from mobile devices that meet data quality standards including temporal frequency and spatial accuracy of anonymized location point observations, temporal coverage and representativeness for the device, and spatial representativeness of the sample. A multi-level weighting method expanded the study sample to county-level estimates. The data extracted for this study included daily estimates of the population staying at home, the population not staying at home, and, when they

leave home, the average number of trips by distance in miles (< 1, 1–3, 3–5, 5–10, 10–25, 25–50, 50–100, 100–250, 250–500, and 500+). Any movement involving a stay of longer than 10 minutes at an anonymized location away from home was considered a trip; multiple stops of longer than 10 minutes before returning home were estimated as multiple trips. This dataset began in January 2019 and data used for this study went from August 31st, 2019 through June 15th, 2021, when the tier system stopped, and California was fully reopened.

Data on the California tier system was downloaded from the California Department of Public Health (CDPH) (42). Each county in California was classified into a tier (1–4) based on indicators of COVID-19 transmission and risk using test positivity and adjusted case rates every week from August 31st, 2020, to June 15th, 2021. All metrics were based on county population size, and adjustments were made for small counties (defined as having less than 106,000 residents), including an exemption from adjusted rates based on testing volume and meeting health equity metrics that specify that test positivity rates in disadvantaged neighborhoods are not different from overall county estimates. Starting April 20th, 2021, absolute case number and vaccine coverage were also considered for moving counties to a less restrictive tier if the prior assessment prevented it from changing tiers. The CDPH assessed case rates and test positivity of the county every Monday and shared classification with counties every Tuesday, which would go into effect the next day (Wednesday). If it was determined that a county needed to move to a more restrictive tier, the county had three days, starting on Wednesday, to implement any changes unless immediate action was merited based on extreme circumstances. A county had to remain in a tier for a minimum of three weeks to advance to a less restrictive tier and could only move forward one tier at a time (even if metrics would indicate skipping tiers).

When a county was considered to have widespread COVID-19 transmission, it was categorized in the most restrictive tier (Purple, tier 1), and key restrictions included keeping social gatherings to a maximum of three households, not allowing indoor seated events, restricting gyms and restaurants to outdoors, and closing bars. In the Red tier (tier 2), when there was considered to be substantial transmission, a maximum of 25 people were allowed to gather outdoors, and indoor gatherings were allowed with modifications, although strongly discouraged. In this tier, gyms were allowed to open at 10% capacity and restaurants at 25% capacity, and bars remained closed. In the 3rd tier (Orange), 50 people were allowed to gather outdoors, gyms opened at 25% capacity and restaurants at 50%, while offices started to open indoors with some modification (although remote work continued to be strongly encouraged); bars also were allowed to open for outdoor use. The least restrictive tier (Yellow, tier 4) allowed outdoor gatherings of up to 100 people, gyms and restaurants open at 50% capacity, and bars to open indoors at 25% capacity. More details about what was allowed or restricted in each tier criteria are provided in the supplementary materials (Table S2).

Analytical strategy

To understand the change in mobility resulting from the California Tier system, we first computed a population-standardized measure for each mobility variable by dividing the population staying at home and the number of trips by the total population (sum of population staying at home and population not

staying at home) and multiplying by 100. These population-standardized measures represent the proportion of people staying home and the average number of daily trips taken for every 100 persons for each distance category. These estimates were averaged at the weekly level for each county, and a difference for every week was computed using 2019 estimates as a baseline to estimate a robust difference as done in previous papers (46, 47). Such robust differences target the mobility pattern that would have been observed in the absence of the California Tier system restrictions for each week in 2020 (using weekly estimates from the previous year). The difference in average mobility at the weekly level was used as the outcome of interest in our models. It should be noted that the 1st of January was considered the first day of the first week of each year, and weekly measures were computed accordingly. With this, weeks started on a different weekday each year (Tuesday in 2019, Wednesday in 2020, and Friday in 2021). The week following the tier system evaluation was used for analysis; for example, the first week where the tier system was evaluated on the 30th of August 2020 corresponded to mobility data from September 2nd to 8th, 2020. A sensitivity analysis was conducted considering the first Wednesday and Friday as the first day of the week, given that the tier system went into effect on Wednesdays, and counties had three days to implement changes when moving into a more restrictive tier.

The county classification every week was collected, and any change to a higher tier level was considered to be less restrictive, while any change to a lower tier level was considered more restrictive. A linear model with fixed effects was applied with the change in tier level as the independent variable and the population-adjusted difference mobility measure as the dependent variable, with fixed effects (for the intercept and the slope) at the county level to compare changes only within each county. The regression coefficients considering the effect of tier system changes on the population not staying at home for each county were extracted for further analysis.

Demographic comparisons

A meta-regression was applied to understand the association between county-level demographics and variation in mobility in response to tier system implementation. County-level demographic data was downloaded from the California State Association of Counties (48), 2019 Census estimates, the California Healthy Places Index (49), and the New York Times recall election results (50). County-level coefficients indicating the effect of a more restrictive tier were regressed with each demographic variable of interest and plotted to explore which characteristics explain the differences in effect observed between counties in California. Variables considered to be potentially related to a tier system response were the number of farms in each county, the gross domestic product (GDP, as a measure of economic activity), median income, economic context (a measure of employment rates, per capita income, and poverty levels), social context (a measure of voter participation and census response), educational context (a measure of preschool enrollment, bachelor's education, and high school enrollment), and the proportion of each county that voted "Yes" to recall Governor Gavin Newsom. Many California residents petitioned for a California Gubernatorial Recall Election as a result of the tier system implemented by Governor Gavin Newsom because of its impacts on the California economy, which required many businesses to shut down or operate at a limited capacity. Census level indicators from the Healthy Places Index were

aggregated to the county level by the calculation of population-weighted means. Data compilation and linear regressions were conducted in STATA 16 SE, while the meta-regression was conducted with R 4.1.0.

Results

Descriptive Statistics

Table 1 provides the descriptive statistics regarding demographics, mobility, and recall vote information averaged for all counties in California. The average GDP is \$51.7 billion, and the average median income is \$77,470 for all counties. On average, there are 4.17 farms per 1,000 people. Over the course of the tier system implementation, an average of 72.87 individuals per 100 people were not staying at home, and the average number of trips that individuals took during the tier system implementation from August 31st, 2020, to June 15th, 2021, was 261.51 per 100 persons. These trips ranged from less than 1 mile which occurred, on average, at a frequency of 64.77 trips per 100 persons, to over 500 miles, which occurred less frequently with an average of 0.26 trips per 100 persons. Most trips (95.4%) remained under 50 miles, and a predominant number of trips were 3 miles or shorter. Across counties, an average of 47.14 percent of persons voted yes for the Gavin Newsom recall. County-specific demographics are presented in the supplementary material (Table S3).

Table 1

Average characteristics of California counties including mobility and county level socio-demographics.

Mobility	Mean (standard deviation)	Demographics	Mean (standard deviation)
Population not staying at home (per 100)	72.87 (5.47)	GDP (billions)	51.7 (119)
Number of trips (per 100 persons)	261.51 (51.28)	Median income	77,470 (22,622)
<1 mile	64.77 (23.04)	# farms/1000 persons	4.17 (8.75)
1–3 miles	64.45 (14.27)	Recall vote	47.14 (16.30)
3–5 miles	29.20 (7.64)	Economic	-0.25 (0.52)
5–10 miles	33.61 (9.72)	Education	-0.23 (0.68)
10–25 miles	38.77 (13.20)	Social	0.22 (0.40)
25–50 miles	18.75 (8.44)	Age 65+	16.4 (3.98)
50–100 miles	8.13 (4.83)		
100–250 miles	3.03 (1.84)		
250–500 miles	0.54 (0.38)		
> 500 miles	0.26 (0.43)		

Figure 1 depicts the changes in tier restrictions across the duration of the California tier system implementation for each county. Many counties began in the more restrictive tiers (red or purple) at the beginning of the tier system implementation, which tended to relax across the ensuing 3–6 weeks. Most counties, except Alpine, Mariposa, and Sierra counties, were in the purple (most restrictive) tier from November 2020 until late March 2021. This coincides with a large portion of the population qualifying to receive the vaccine, and most counties except for Del Norte, Shasta, and Yuba counties were in the less restrictive tiers (yellow and orange) by the time the tier system was retired on June 15, 2021.

Geographic Differences in Mobility

Generally, moving to a more restrictive tier led to a decrease in mobility (i.e., population not staying home), while a less restrictive tier increased mobility, as intended (Fig. 2). Regions such as Northern California, particularly in the Bay Area and the Eastern Sierras, as well as counties along most of the coastline had a greater decrease in mobility following a change to a more restrictive tier. The counties with the largest decrease in mobility (6–7 staying at home per 100 persons) after moving to a more restrictive tier include Marin and Placer counties (Fig. 2a). In contrast, the counties that showed the smallest decrease in mobility (0–3 staying at home per 100 persons) after a change to a more restrictive

tier were Del Norte, Modoc, Trinity, Tehama, Plumas, Sutter, Inyo, Kings, and Riverside counties. It is important to note that some counties, such as Los Angeles, remained in the purple tier (most restrictive) for several months and then gradually loosened restrictions but were never reclassified to a more restrictive tier, and therefore could not be analyzed for the increased restrictions change; these counties appear as missing in the map (Fig. 2b).

Differences were observed in trends of increased mobility after moving to a less restrictive tier, although these estimates are less precise. The highest increases in mobility occurred along the northern California coastline, northeastern Shasta Cascades region, the northern Sierra Nevada region, and Southern California. In cases where counties went to the least restrictive tier, the counties that most increased their mobility (greater than 5 staying at home per 100 persons) were Imperial, Mono, Sonoma, and Santa Cruz. Counties that had the smallest increase in mobility (0-2.5 staying at home per 100 persons) were Ventura, San Benito, Tulare, Napa, and Del Norte.

Differences by Trips

The changes in mobility varied by the distance of the trips analyzed, as shown in Fig. 3. For changes to a more restrictive tier, the number of trips between 10–25 miles per 100 people greatly decreased along with the number of trips between 5–10 miles, 3–5 miles, and 1–3 miles. The most significant decrease was in trips less than 1 mile, however, which decreased by an average of 20 daily trips per 100 people. Interestingly, longer trips of 50–100 miles and 100–250 miles were shown to increase following changes to a more restrictive tier. When shifting to a less restrictive tier, there was little change in longer trips of greater than 25 miles per 100 people. In the medium range of trips of 3–5, 5–10, and 10–25 miles in distance, however, there was an increase in each of these categories by approximately 2–3 trips per 100 people. Sensitivity analyses using Wednesdays or Fridays as the first day of the week showed similar results (Table S4 & S5).

Changes in Mobility by Demographic Characteristics

Demographics at the county level were associated with the degree of change in mobility observed after moving to a more restrictive tier. As the GDP of a county increases, counties have a greater change in mobility patterns from a tier system restriction (Fig. 4). Median income had a similar association; counties with a higher income had a greater decrease in mobility when moving to a more restrictive tier. The economic, social, and educational context of a county was also associated with a greater change in mobility following tier restrictions. The number of farms per 1000 persons showed a positive association, indicating that when a county has more farms, there was less change in mobility, although this estimate was imprecise (Fig. 4). The proportion of the county that voted for the governor recall also appeared to have a positive association; as the percentage of the county voting yes increased, the change in their mobility patterns was lessened, meaning that counties voting predominantly in favor of the recall were less likely to decrease their mobility when shifting to a more restrictive tier. Lastly, the proportion of persons 65 years and older in a county did not appear to be associated with a greater change in mobility following tier restrictions.

Discussion

The tier-system implemented by California to restrict mobility during the COVID-19 pandemic was associated with an overall decrease in mobility when counties shifted to a more restrictive tier, and increased mobility when they shifted to a less restrictive tier. We identified that shorter and medium range trips greatly decreased with changes to a more restrictive tier, whereas only medium trips increased noticeably when moving to a less restrictive tier. Surprisingly, we found that longer trips between 50 and 250 miles increased following a change to a more restrictive tier. Furthermore, important geographic differences across counties regarding mobility patterns were identified, where Northern California and the coastline had a greater decrease in mobility when moving to a more restrictive tier. These differences were in part explained by socio-demographic variations between counties. At the county level, higher GDP, higher education, higher economic context, higher social context, higher income, lower number of farms, and lower percentage of voting yes on the governor recall were associated with a greater impact on mobility. Overall, the tier system proved to be an effective policy in managing mobility, with counties generally changing their mobility patterns following a change in tier status.

We found that the tier system was effective in impacting mobility, reducing the population not staying at home by -4.45 [-5.44, -3.47] per 100 persons when counties moved to a more restrictive tier (Table S4). However, when counties moved to a less restrictive tier, the population staying at home increased by only 0.57 [-0.08, 1.22] per 100 persons, with imprecise results (Table S5). This indicates that even when restrictions loosen, counties may not revert back to original mobility patterns immediately (51, 52). Risk perception may play an important role in the willingness of populations to continue to implement protective measures, even with easing of restrictions (53, 54). This can also help explain the spatial variation in mobility changes throughout the state, as some counties may have the capacity and resources to maintain more conservative behaviors with regards to COVID-19 (Fig. 3) (43). The results of this study provide insight into the potential impacts of implementing a spatially derived policy, like the tier-system, in efforts to combat dynamic public health emergencies.

The effectiveness of the California tier system policy also varied by distance of the trips traveled. Overall, the daily number of trips decreased by -36.7 [-56.3, -17.0] per 100 persons when moving to a more restrictive tier, with strongest reductions in lower distance trips of 25 miles or less (Table S4). However, results also indicate unintended consequences of this policy as moving to a more restrictive tier increased trips from 50 to 250 miles (Fig. 3). This reverse effect may be explained by residents traveling to neighboring counties when moving to a more restrictive tier to avoid restrictions. This differs from some of the existing research showing that lockdowns have a stronger reduction in long-range mobility than short-range trips (13, 29). However, previous work on this topic has been limited and varied; Pullano and colleagues identified that lockdown was associated with decreases in shorter trips in France (29), whereas Schlosser and colleagues found that in Germany, long distance trips decreased more strongly than short distance trips following the COVID-19 lockdown (55). This may be due to differences between the tier system and full lockdown measures evaluated in prior studies. The unintended consequences of the tier system may also be due to limited enforcement. The California tier system was enforced more

strictly for businesses, but there was limited enforcement concerning individual adherence to the stay-at-home orders and recommendations to halt travel (Table S2). California did not enforce the law to the same degree other parts of the world did, such as France issuing fines for violations against the home confinement orders and lockdown restrictions (29). Taken together, this may explain the opposite observed effect of an increase in longer trips. These unintended effects are critical to understanding how the population responded to the policy and to better prepare for future measures to reduce mobility.

The variation in mobility reduction from the tier system between counties in California provides insight into how the policy could be adapted to the demographics of sub-populations to maximize effectiveness. We found that as the county GDP and median income increased, the tier system had a greater impact on mobility. Similarly, as the social, education, and economic context of a county increased based on indicators from the Healthy Places Index (56), mobility had a greater decrease following the change to a more restrictive tier (Fig. 4). Several studies have identified higher compliance with COVID-19 policies among regions with higher income and increased access to resources (22–24, 27, 28, 57–59). It is important to note that many frontline workers lacked the ability to shelter in place, which in turn increased their risk of contracting, and spreading, the virus (60). Similar to our results, it has been shown in other studies that areas with lower income had less of a reduction in population mobility during the pandemic (61). This could potentially be due to the percentages of frontline and essential workers in lower-income communities compared to higher-income jobs that can allow options for remote work. These differences can be partially explained by a mobility adaptation disparity since higher-paying jobs have increased flexibility to work from home when compared to essential positions that dominate the job sector in lower-income counties (57). We also found that the county-level recall election results were associated with tier system response. In other words, counties voting for the recall were less likely to have a decrease in mobility when moving to a more restrictive tier (Figure S1). In California, the recall election emerged in part as a result of the opposition to the Governor's COVID-19 policies, including the tier system. The consideration of politics is critical to understanding the effects of COVID-19 policies, as the social and political economy are key to shaping compliance to public health measures (62).

Similarly, although the results were not precise, we did find that the number of farms was associated with less of a reduction in mobility when moving to a more restrictive tier (Fig. 4). Farmworkers were shown to be particularly affected by COVID-19 (63). This may be due to the essential nature of agricultural work; farmworkers were expected to continue working despite tier system restrictions (64). This population is particularly vulnerable as they tend to have lower incomes, and many are ineligible for unemployment and other benefits. The exploitative work conditions and lack of social protections are important to consider when understanding differing responses to the tier system (64, 65). Essential workers comprise 26% of the working-age population, and nearly 50% are from minority racial and ethnic groups. Minority groups are also at greater risk of numerous chronic diseases that are also linked to worse COVID-19 outcomes (43). This is crucial to study as frontline workers and lower-income communities can have higher exposure rates to the virus, driving further health disparities and inequities. COVID-19 measures tailored and adapted to these vulnerable populations are necessary to effectively and equitably implement policies and limit viral spread (36, 43, 66).

There are limitations to this study that are important to acknowledge. First, as the mobility dataset started in 2019, we only had one year to draw comparisons. Ideally, we would have had more years to use as a baseline mobility measure, but we feel contrasting 2020 and 2021 to 2019 remains useful, as 2019 was not affected by the pandemic or related policies. Second, the mobility data used is experimental, and data quality standards may be lacking. By comparing mobility within each county using the same data source, we feel the data are sufficiently reliable for the purpose of this study. Also, any residents that do not own or go out with a mobile phone will be excluded from the sample; this could produce a bias as, for example, older persons may be less likely to own or travel with mobile phones; phone behaviors may have also changed because of the pandemic. Moreover, any trip that did not have a pause of 10 minutes or more away from home would not be captured. We also relied on measures of mobility at the county level, and effects may vary within counties; we hope to explore within county variability using more spatially resolved estimates in future work but are currently limited by county-level estimates. Lastly, the effects of the pandemic coincided with wildfires and heat waves that affected the state during the summer and fall of 2020, which could also impact mobility; in future work, it would be interesting to disentangle the specific effect of these events.

In conclusion, we found strong evidence that the California tier system and associated restrictions were effective in decreasing population mobility. However, results also showed unintended effects of increased travel for longer trips when moving to a more restrictive tier, which is important to consider when developing and implementing future policies. It may indicate that greater coordination is required between neighboring counties. There was also spatial variation in the effectiveness of this policy, which can be partially explained by differences in economic activity and political opinions across the state. It is important to understand this heterogeneity in the response to the California tier system policy to adapt it to maximize equity and effectiveness. To our knowledge, this was the first study assessing the impact of the tier system policy in California on mobility patterns during its complete duration and how these mobility patterns differed by various county-level characteristics. Results provide evidence that the regional tier system classification was effective in limiting population mobility during a pandemic. Evaluating the strengths and weaknesses of COVID-19 response policies is informative for other states and countries to increase preparedness and to inform effective policies for future global health emergencies.

Declarations

Ethics approval and consent to participate

Not applicable as the manuscript used solely publicly available data sources.

Consent for publication

Not applicable

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available in the GitHub repository, https://github.com/benmarhnia-lab/CA_tier_system_mobility.git.

Competing interests

The authors declare no competing interests.

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Authors' contributions

LS conducted the analysis. ES, LS, and AT wrote the main manuscript text. KC and TB discussed the results and contributed to the final paper. All authors reviewed and approved the manuscript.

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References

1. Belik V, Geisel T, Brockmann D. Natural human mobility patterns and spatial spread of infectious diseases. *Phys Rev X*. 2011;1(1):11001.
2. Aleta A, Martin-Corral D, y Piontti AP, Ajelli M, Litvinova M, Chinazzi M, et al. Modelling the impact of testing, contact tracing and household quarantine on second waves of COVID-19. *Nat Hum Behav*. 2020;4(9):964–71.
3. Huang IY. Fighting COVID-19 through government initiatives and collaborative governance: the Taiwan experience. *Public Adm Rev*. 2020;80(4):665–70.
4. Wang Y. Government policies, national culture and social distancing during the first wave of the COVID-19 pandemic: International evidence. *Saf Sci*. 2021;135:105138.
5. Lasry A, Kidder D, Hast M, Poovey J, Sunshine G, Winglee K, et al. Timing of community mitigation and changes in reported COVID-19 and community mobility—four US metropolitan areas, February 26–April 1, 2020. *Morb Mortal Wkly Rep*. 2020;69(15):451.
6. Shewry S, Pan ES. Regional stay at home order. 2020.
7. Fowler JH, Hill SJ, Levin R, Obradovich N. The effect of stay-at-home orders on COVID-19 cases and fatalities in the United States. *arXiv Prepr arXiv200406098*. 2020;
8. Sen S, Karaca-Mandic P, Georgiou A. Association of stay-at-home orders with COVID-19 hospitalizations in 4 states. *Jama*. 2020;323(24):2522–4.

9. Badr HS, Du H, Marshall M, Dong E, Squire MM, Gardner LM. Association between mobility patterns and COVID-19 transmission in the USA: a mathematical modelling study. *Lancet Infect Dis.* 2020;20(11):1247–54.
10. Cartenì A, Di Francesco L, Martino M. How mobility habits influenced the spread of the COVID-19 pandemic: Results from the Italian case study. *Sci Total Environ.* 2020;741:140489.
11. Friedson AI, McNichols D, Sabia JJ, Dave D. Shelter-in-place orders and public health: evidence from California during the COVID-19 pandemic. *J Policy Anal Manag.* 2021;40(1):258–83.
12. Nouvellet P, Bhatia S, Cori A, Ainslie KEC, Baguelin M, Bhatt S, et al. Reduction in mobility and COVID-19 transmission. *Nat Commun.* 2021;12(1):1–9.
13. Pepe E, Bajardi P, Gauvin L, Privitera F, Lake B, Cattuto C, et al. COVID-19 outbreak response, a dataset to assess mobility changes in Italy following national lockdown. *Sci data.* 2020;7(1):1–7.
14. Redding SJ, Glaeser EL, Gorback C. How Much Does COVID-19 Increase with Mobility? Evidence from New York and Four Other US Cities. 2020;
15. Guan G, Dery Y, Yechezkel M, Ben-Gal I, Yamin D, Brandeau ML. Early detection of COVID-19 outbreaks using human mobility data. *PLoS One.* 2021;16(7):e0253865.
16. Tokey AI. Spatial association of mobility and COVID-19 infection rate in the USA: A county-level study using mobile phone location data. *J Transp Heal.* 2021;22:101135.
17. Huang X, Shao X, Xing L, Hu Y, Sin DD, Zhang X. The impact of lockdown timing on COVID-19 transmission across US counties. *EClinicalMedicine.* 2021;38:101035.
18. Oh J, Lee H-Y, Khuong QL, Markuns JF, Bullen C, Barrios OEA, et al. Mobility restrictions were associated with reductions in COVID-19 incidence early in the pandemic: evidence from a real-time evaluation in 34 countries. *Sci Rep.* 2021;11(1):1–17.
19. He S, Lee J, Langworthy B, Xin J, James P, Yang Y, et al. Delay in the effect of restricting community mobility on the spread of COVID-19 during the first wave in the United States. In: *Open forum infectious diseases.* Oxford University Press US; 2022. p. ofab586.
20. Xiong C, Hu S, Yang M, Younes H, Luo W, Ghader S, et al. Mobile device location data reveal human mobility response to state-level stay-at-home orders during the COVID-19 pandemic in the USA. *J R Soc Interface.* 2020;17(173):20200344.
21. Wellenius GA, Vispute S, Espinosa V, Fabrikant A, Tsai TC, Hennessy J, et al. Impacts of social distancing policies on mobility and COVID-19 case growth in the US. *Nat Commun.* 2021;12(1):1–7.
22. Chiou L, Tucker C. Social distancing, internet access and inequality. *National Bureau of Economic Research*; 2020.
23. Coven J, Gupta A. Disparities in mobility responses to COVID-19. *New York Univ.* 2020;
24. Engle S, Stromme J, Zhou A. Staying at home: mobility effects of covid-19. Available SSRN 3565703. 2020;
25. Warren MS, Skillman SW. Mobility changes in response to COVID-19. *arXiv Prepr arXiv200314228.* 2020;

26. Kraemer MUG, Yang C-H, Gutierrez B, Wu C-H, Klein B, Pigott DM, et al. The effect of human mobility and control measures on the COVID-19 epidemic in China. *Science* (80-). 2020;368(6490):493–7.
27. Borkowski P, Jażdżewska-Gutta M, Szmelter-Jarosz A. Lockdowned: Everyday mobility changes in response to COVID-19. *J Transp Geogr*. 2021;90:102906.
28. Bonaccorsi G, Pierri F, Cinelli M, Flori A, Galeazzi A, Porcelli F, et al. Economic and social consequences of human mobility restrictions under COVID-19. *Proc Natl Acad Sci*. 2020;117(27):15530–5.
29. Pullano G, Valdano E, Scarpa N, Rubrichi S, Colizza V. Evaluating the effect of demographic factors, socioeconomic factors, and risk aversion on mobility during the COVID-19 epidemic in France under lockdown: a population-based study. *Lancet Digit Heal* [Internet]. 2020;2(12):e638–49. Available from: <https://www.sciencedirect.com/science/article/pii/S2589750020302430>
30. Santamaria C, Sermi F, Spyrtatos S, Iacus SM, Annunziato A, Tarchi D, et al. Measuring the impact of COVID-19 confinement measures on human mobility using mobile positioning data. A European regional analysis. *Saf Sci*. 2020;132:104925.
31. Szocska M, Pollner P, Schiszler I, Joo T, Palicz T, McKee M, et al. Countrywide population movement monitoring using mobile devices generated (big) data during the COVID-19 crisis. *Sci Rep*. 2021;11(1):1–9.
32. Chakraborty M, Shakir Mahmud M, Gates TJ, Sinha S. Analysis and Prediction of Human Mobility in the United States during the Early Stages of the COVID-19 Pandemic using Regularized Linear Models. *Transp Res Rec*. 2022;03611981211067794.
33. Beria P, Lunkar V. Presence and mobility of the population during the first wave of Covid-19 outbreak and lockdown in Italy. *Sustain Cities Soc*. 2021;65:102616.
34. Nikiforiadis A, Mitropoulos L, Kopelias P, Basbas S, Stamatiadis N, Kroustali S. Exploring mobility pattern changes between before, during and after COVID-19 lockdown periods for young adults. *Cities*. 2022;103662.
35. Manica M, Guzzetta G, Riccardo F, Valenti A, Poletti P, Marziano V, et al. Impact of tiered restrictions on human activities and the epidemiology of the second wave of COVID-19 in Italy. *Nat Commun*. 2021;12(1):1–9.
36. Marwah A, Feldman J, Moineddin R, Thomas A. Population Mobility and Socioeconomic Indicators in California, USA and Ontario, Canada during the COVID-19 Pandemic. *Int J Infect Dis*. 2022;116:S25–6.
37. Dainton C, Hay A. Quantifying the relationship between lockdowns, mobility, and effective reproduction number (R_t) during the COVID-19 pandemic in the Greater Toronto Area. *BMC Public Health*. 2021;21(1):1–8.
38. Dzobo M, Hlongwa M, Denhere K, Kampira V, Mugoni M, Musuka G, et al. COVID-19 resurgence: lessons learnt to inform the South African response. *Disaster Med Public Health Prep*. 2021;1–17.
39. Ge J, He D, Lin Z, Zhu H, Zhuang Z. Four-tier response system and spatial propagation of COVID-19 in China by a network model. *Math Biosci*. 2020;330:108484.

40. The Traffic Light Model [Internet]. 2021. Available from: <https://corona.health.gov.il/en/ramzor-model/>
41. Largent EA, Persad G, Mello MM, Wenner DM, Kramer DB, Tucker Edmonds B, et al. Incorporating Health Equity Into COVID-19 Reopening Plans: Policy Experimentation in California. *Am J Public Health*. 2021;(0):e1–8.
42. Blueprint for a Safer Economy [Internet]. California Department of Public Health. 2021. Available from: <https://www.cdph.ca.gov/Programs/CID/DCDC/Pages/COVID-19/COVID19CountyMonitoringOverview.aspx>
43. Reitsma MB, Claypool AL, Vargo J, Shete PB, McCorvie R, Wheeler WH, et al. Racial/Ethnic Disparities In COVID-19 Exposure Risk, Testing, And Cases At The Subcounty Level In California: Study examines racial/ethnic disparities in COVID-19 risk, testing, and cases. *Health Aff*. 2021;40(6):870–8.
44. Tai DBG, Shah A, Doubeni CA, Sia IG, Wieland ML. The disproportionate impact of COVID-19 on racial and ethnic minorities in the United States. *Clin Infect Dis*. 2021;72(4):703–6.
45. Changes in Mobility by State [Internet]. Bureau of Transportation Statistics. 2021. Available from: <https://www.bts.gov/browse-statistical-products-and-data/covid-related/changes-mobility-state-0>
46. Bekbulat B, Apte JS, Millet DB, Robinson AL, Wells KC, Presto AA, et al. Changes in criteria air pollution levels in the US before, during, and after Covid-19 stay-at-home orders: Evidence from regulatory monitors. *Sci Total Environ*. 2021;769:144693.
47. Benmarhnia T. Linkages between air pollution and the health burden from COVID-19: methodological challenges and opportunities. *Am J Epidemiol*. 2020;189(11):1238–43.
48. Data and Research [Internet]. California State Association of Counties. 2021. Available from: <https://www.counties.org/data-and-research>
49. California Healthy Places Index [Internet]. Public Health Alliance of Southern California. 2022. Available from: <https://www.healthyplacesindex.org/>
50. California Recall Election Results [Internet]. New York Times. 2021. Available from: <https://www.nytimes.com/interactive/2021/09/14/us/elections/results-california-recall.html>
51. Christidis P, Christodoulou A, Navajas-Cawood E, Ciuffo B. The Post-Pandemic Recovery of Transport Activity: Emerging Mobility Patterns and Repercussions on Future Evolution. Vol. 13, Sustainability. 2021.
52. Bönisch S, Wegscheider K, Krause L, Sehner S, Wiegel S, Zapf A, et al. Effects of Coronavirus Disease (COVID-19) Related Contact Restrictions in Germany, March to May 2020, on the Mobility and Relation to Infection Patterns [Internet]. Vol. 8, *Frontiers in Public Health*. 2020. p. 619. Available from: <https://www.frontiersin.org/article/10.3389/fpubh.2020.568287>
53. Bruine de Bruin W, Bennett D. Relationships Between Initial COVID-19 Risk Perceptions and Protective Health Behaviors: A National Survey. *Am J Prev Med* [Internet]. 2020;59(2):157–67. Available from: <https://www.sciencedirect.com/science/article/pii/S0749379720302130>
54. Chan HF, Skali A, Savage DA, Stadelmann D, Torgler B. Risk attitudes and human mobility during the COVID-19 pandemic. *Sci Rep* [Internet]. 2020;10(1):19931. Available from:

<https://doi.org/10.1038/s41598-020-76763-2>

55. Schlosser F, Maier BF, Jack O, Hinrichs D, Zachariae A, Brockmann D. COVID-19 lockdown induces disease-mitigating structural changes in mobility networks. *Proc Natl Acad Sci* [Internet]. 2020 Dec 29;117(52):32883 LP – 32890. Available from: <http://www.pnas.org/content/117/52/32883.abstract>
56. Maizlish N, Delaney T, Dowling H, Chapman DA, Sabo R, Woolf S, et al. California healthy places index: frames matter. *Public Health Rep*. 2019;134(4):354–62.
57. Dueñas M, Campi M, Olmos LE. Changes in mobility and socioeconomic conditions during the COVID-19 outbreak. *Humanit Soc Sci Commun* [Internet]. 2021;8(1):101. Available from: <https://doi.org/10.1057/s41599-021-00775-0>
58. Sun Q, Zhou W, Kabiri A, Darzi A, Hu S, Younes H, et al. COVID-19 and Income Profile: How People in Different Income Groups Responded to Disease Outbreak, Case Study of the United States. *arXiv Prepr arXiv200702160*. 2020;
59. Iio K, Guo X, Kong X, Rees K, Bruce Wang X. COVID-19 and social distancing: Disparities in mobility adaptation between income groups. *Transp Res Interdiscip Perspect* [Internet]. 2021;10:100333. Available from: <https://www.sciencedirect.com/science/article/pii/S2590198221000403>
60. Dasgupta N, Jonsson Funk M, Lazard A, White BE, Marshall SW. Quantifying the social distancing privilege gap: a longitudinal study of smartphone movement. Available SSRN 3588585. 2020;
61. Garnier R, Benetka JR, Kraemer J, Bansal S. Socioeconomic disparities in social distancing during the COVID-19 pandemic in the United States: observational study. *J Med Internet Res*. 2021;23(1):e24591.
62. Greer SL, King EJ, da Fonseca EM, Peralta-Santos A. The comparative politics of COVID-19: The need to understand government responses. *Glob Public Health* [Internet]. 2020 Sep 1;15(9):1413–6. Available from: <https://doi.org/10.1080/17441692.2020.1783340>
63. Lusk JL, Chandra R. Farmer and farm worker illnesses and deaths from COVID-19 and impacts on agricultural output. *PLoS One* [Internet]. 2021 Apr 28;16(4):e0250621. Available from: <https://doi.org/10.1371/journal.pone.0250621>
64. Beatty T, Hill A, Martin P, Rutledge Z. COVID-19 and farm workers: challenges facing California agriculture. *ARE Updat*. 2020;23(5):2–4.
65. Handal AJ, Iglesias-Ríos L, Fleming PJ, Valentín-Cortés MA, O'Neill MS. “Essential” but Expendable: Farmworkers During the COVID-19 Pandemic—The Michigan Farmworker Project. *Am J Public Health* [Internet]. 2020 Nov 12;110(12):1760–2. Available from: <https://doi.org/10.2105/AJPH.2020.305947>
66. Hu S, Xiong C, Younes H, Yang M, Darzi A, Jin ZC. Examining spatiotemporal evolution of racial/ethnic disparities in human mobility and COVID-19 health outcomes: Evidence from the contiguous United States. *Sustain cities Soc*. 2022;76:103506.

Supplementary Materials

The Supplementary Materials are not available with this version

Figures

Figure 1

California tier changes by county from August 31st, 2020, to June 15th 2021 during implementation of the Blueprint for a Safer Economy (tier system).

Change in Population not staying at home

a)

More Restrictive Tier

b)

Less Restrictive Tier

Figure 2

Change in the mobility (population not staying at home per 100 persons) in California counties associated with moving to a more restrictive tier (a) or less restrictive tier (b).

Figure 3

Change in mobility (average daily trips per 100 persons) related to tier system change by the distance of trip in miles.

Figure 4

Results of meta-regression showing the association between interquartile range increases in county demographic characteristics (y-axis) and mobility decrease (x-axis) from tier system restrictions in California. Values greater than 0 indicate a greater change in mobility, while values less than 0 indicate a lesser change in mobility.