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Characterizing Spatial Accessibility of COVID-19 Testing and Vaccination Sites using Dasymetric Mapping and GIS

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Abstract: The COVID-19 pandemic accentuated existing health disparities in the U.S., inflicting staggeringly disproportionate rates of exposure, infection and death among racial and ethnic minority populations. Early evidence in 2020 had suggested that testing locations were not equitably accessible to racial/ethnic minority populations, and thus, increased the likelihood of unnoticed virus spread in minority communities. Additionally, racial/ethnic minority populations have been less likely to be vaccinated for COVID-19 as of February 2021, when vaccination had just started rolling out. In this study, we use Intelligent Dasymetric Mapping (IDM) and GIS Service Area analysis to examine spatial access to testing and vaccination sites in the Denver metropolitan area in January 2021, when testing and vaccination access was limited and competitive. Our results indicate that the racial/ethnic composition in total service areas with short walking- or driving-travel times was similar to the expected racial/ethnic composition of the Denver metro area, with minority populations slightly overrepresented in the total service areas. To ensure equitable vaccination and testing in minority communities in the future, in addition to ensuring spatial access, policymakers and health officials should increase community outreach, establish trust, and lower potential costs. Our study demonstrates the value of IDM in studying public health access.

Keywords: GIS, COVID-19, Vaccination, Testing, Disparity, Accessibility, Dasymetric mapping

1. Introduction

The COVID-19 pandemic impacted racial and ethnic minority populations in the U.S. disproportionately, accentuating existing health disparities. This disproportionate impact stems from increased levels of exposure, social vulnerability, comorbidities, and systemic disparities in the healthcare system, including health care access and insurance coverage (Chowkwanyun et al., 2020; Ravi, 2020; Sun et al., 2020). Hispanic and Latinx communities are more likely to work in essential industries (that do not lend themselves to remote work), work while ill due to inadequate sick leave or medical insurance, live in larger household sizes or community housing, and face delays in testing after symptom onset (Piper et al., 2017; Podewils et al., 2020). African Americans are more likely to live in crowded, multigenerational homes and neighborhoods with higher housing densities, have limited access to health care and insufficient insurance coverage, and work in public-facing jobs (Burström et al., 2020; Rollston et al., 2020; Webb Hooper et al., 2020). In addition to the elevated social vulnerability of racial/ethnic minorities, the higher prevalence of biological comorbidities such as diabetes, hypertension, chronic kidney disease, cardiovascular disease and obesity aggravated the COVID-19 disease burden on communities of color (Zheng et al., 2020).

According to a report by the National Vital Statistics System, deaths per week in 2020 increased over the 2015-2019 average with staggeringly disproportionate figures for racial and ethnic minority populations, with Hispanic/Latinx at 53.6%, Asian at 36.6%, Black/African American at 32.9%, compared to 11.9% for the White population (Rossen et al., 2020). The disparities observed at the national level were also manifest in the State of Colorado and its largest city and Capital, Denver, where Hispanic adults suffered the majority of adult cases (54.8%), hospitalizations (62%), and deaths (51%), more than double the overall proportion of Hispanic adults in Denver (24.9%) (Podewils et al., 2020).

Prior to the availability of approved vaccines, testing and subsequent isolation and contact tracing were among the most effective nonpharmaceutical interventions (including masking and social distancing) for curbing the spread of the virus. However, early evidence indicated a considerable racial gap in spatial access (measured through distance) to testing sites in U.S. cities, with sites primarily serving White and affluent neighborhoods (Kim et al., 2020). Another early study in New York City showed that populations in lower income neighborhoods or communities of color were less likely to be tested, even though they were more likely to test positive for the disease (Lieberman-Cribbin et al., 2020).

With the increased availability of testing and the limited rollout of vaccines in early 2021, the U.S. continued to break records in new cases and hospitalizations, with approximately 2.3 million cases recorded only in the second half of January 2021. As of February 1, 2021, approximately 31 million doses of COVID-19 vaccines

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were administered, largely to medical health workers and some elderly residents. However, racial/ethnic minority populations were less likely to be vaccinated for COVID-19 in Colorado. As of February 1, 2021, approximately 71% of those vaccinated in the state were White, just under 2% Black, and just under 5% Hispanic, while the state's demographic composition was ~67% White, ~4%Black, and ~21% Hispanic (Dukakis, 2021). Among Colorado residents of 70 years old and older, the priority population for vaccination at the time these statistics were released, 10.2% and 2.6% were Hispanic and Black, respectively (CDPHE, 2021a), indicating a racial gap.

Given the disproportionate health outcomes of COVID-19, it was crucial that racial/ethnic minorities have equitable or better than average access to testing and vaccination upon availability, especially given their lower overall trust in the vaccine due to historical reasons (Rouw et al., 2020). Although equitable spatial access may not be sufficient, it is indeed a prerequisite for ensuring vaccination and testing of racial/ethnic minorities, provided that adequate education, outreach and encouragement is undertaken.

Geographic Information Systems (GIS) and spatial analysis have been widely leveraged in studying the geographic aspects of social determinants of health. Exemplar applications related to this study include the identification of gaps and barriers in geographic coverage of healthcare (Edward et al., 2017), multi-criteria modeling and suitability analysis for point-of-care site selection (Dell'Ovo et al., 2018; Oppio et al., 2016), and uncovering disparities in healthcare capacity in relation to the population served (Ge et al., 2021; Luo et al., 2003).

From a technical perspective, various spatial analysis methods within the GIS environment have been leveraged for these purposes, including variations of service area analysis for studying geographic coverage using distance (Hawthorne et al., 2012), or catchment methods and gravity models for studying accessibility from both distance and capacity points of view (Ge et al., 2021; Luo et al., 2003; Yang et al., 2006), multi-criteria modeling (Halder et al., 2020) or location-allocation (Polo et al., 2015) for analyzing suitability of (new) sites.

Most studies leveraging GIS and spatial analysis for examining levels of access to healthcare rely on spatial aerial units containing aggregated population counts, such as Census Block Groups (CBGs), Census Tracts, or counties, depending on the level of analysis. The centroid location of spatial units and count of population in the units (i.e., demand) are then compared to the location and capacity of health care providers (i.e., supply) to characterize levels of access in the aggregate spatial units. At the core of such GIS analyses is the measurement of distance between the point-of-care and the centroid location of spatial units, i.e., the areal (polygon) units for which population counts are available. However, the size and shape of these spatial units vary, with some units spanning vast areas, which may include uninhabited, wilderness or non-residential lands. This is the case even for CBGs, the smallest spatial units used by the Census Bureau for publishing population characteristics.

The use of large, aggregate spatial units for characterizing accessibility may lead to biased or imprecise results in the derived level of accessibility. We argue that for health care services that are needed on a frequent basis, or services that are crucial to the overall functions of a society, a more precise characterization of demand populations' location is necessary. Such crucial services include testing and vaccination during a pandemic. Frequent testing is essential for curbing the spread of a disease, and therefore, equitable and efficient accessibility of testing locations is of utmost importance. Similarly, ensuring accessible vaccination sites, especially among population groups who are more vulnerable to the disease, and/or less likely to receive the vaccine in a timely manner (Dukakis, 2021; KFF, 2021; Rouw et al., 2020), increases the chances of a successful vaccination campaign. To obtain a more accurate picture of population spatial distribution, a GIS technique called *Dasymetric mapping*—a technique to re-distribute attribute values in larges area into more accurate distributions within those units (Maantay et al., 2007)—can be used to redistribute aggregate populations using ancillary information, such as residential areas or developed land (Eicher et al., 2001; Mennis, 2009; Mennis et al., 2006). The refined population distribution can then be used in various spatial analyses for measuring access to healthcare facilities, including identifying populations residing in *Service Area* of facilities, i.e., the region encompassing street networks around facilities that can be accessed within a given distance or travel-time.

In this article, we use dasymetric mapping and service area analysis to characterize the accessibility of COVID-19 testing and vaccination sites in the Denver Metro Area in Colorado, U.S. by different racial and ethnic groups during the crucial period of January 2021 when vaccines became available to the public, and testing became more accessible. We use maximum travel times as the proxy for level of access to the sites. The travel times are estimated by taking into account the usual local traffic conditions, speed limits, street geometry, and barriers. We construct service areas with several walking or driving travel-time thresholds, and compare the racial/ethnic composition of the service areas with the expected demographic composition in the Denver metro area. To count the populations living in the service areas, we use dasymetric mapping with residential parcel data as ancillary information to obtain realistic patterns of population distribution. Our null hypothesis is that racial and ethnic minority populations are not underrepresented in the service areas. The null hypothesis indicates equitable spatial distribution of the sites.

2. Methods

Figure 1 outlines the steps and GIS operations undertaken in our analysis. We elaborate on the details of our methods in the rest of this section.

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2.1 Study Area and Data

Study area: We focus our study on the metropolitan area of Denver, Colorado, U.S., which includes the continuous region spanning the six counties of Adams, Arapahoe, Broomfield, Denver, Douglas, and Jefferson in Colorado, United States of America.

COVID-19 testing sites: We retrieved a dataset of diagnostic testing sites in the study area from the Tri-county Health Department website as of January 14, 2021 (Tri-County Health, 2021). A downloadable web map was made available by the Health Department, which in addition to the locations of testing sites, included an attribute on the cost of testing at each site. Since our study is focused on the accessibility of sites, we chose to subset the dataset to include only the testing sites marked as free or having no out-of-pocket costs after insurance. These testing sites did not require a referral from a healthcare professional, and were open to the general public. Also, we only included testing sites offering diagnostic tests, and not the ones offering only antibody tests. Antibody tests are not meant for diagnosis, and cannot determine when the individual was infected, or if they are currently infected. Subsetting the data resulted in 38 diagnostic testing sites in the study area. It is worth noting that we compared the Tri-county Health Department dataset to the one provided by the Colorado Department of Public Health & Environment (CDPHE), which for the time period of this study, was out of date, and listed considerably fewer testing sites in the study area. We contacted the GIS and health departments of the counties in the study area as well as CDPHE, but could not retrieve information on the daily capacity of the testing sites at the time. Although the Tri-county Health Department officially serves only Adams, Arapahoe and Douglas counties, it had the most up-to-date and comprehensive list of vaccination sites for our entire study area spanning the six counties.

COVID-19 vaccination sites: We generated a GIS dataset of vaccine providers in the study area using the information provided by the CDPHE public website for January 14, 2021 (CDPHE, 2021b). Specifically, CDPHE published a document listing the name of each vaccine provider by county across Colorado. We used Google Earth to locate the geographic location of each vaccine provider by name, confirmed the match to the intended name manually, and exported the geographic coordinates for each site. We then compiled and exported the locations as a Keyhole Markup Language (KML) file. We identified a total of 81 geolocated vaccination sites in the study area. No information was available on the capacity of the vaccination sites during the period of our study. The vaccine was made available free of charge for all Colorado residents, regardless of insurance status (CDPHE, 2021b).

Population data: We retrieved Census Block Group (CBG)-level GIS layers of the American Community Survey demographic characteristics from the Colorado's Department of Local Affairs (CDLA, 2020). We used the total population count at the CBGs (field name pop1418), as well as the counts for specific racial and ethnic groups in each CBG including Hispanic, White_nh (non-Hispanic White), Black_nh (non-Hispanic Black), Asian_nh (non-Hispanic Asian), and ntvam_nh (non-Hispanic Native American). Table 1 provides summary statistics for the CBGs.

Population	Total in study area	Avg. per CBG	Std. per CBG
White	1,791,572 (65.70%)	1,013	718
Hispanic	652,657 (23.93%)	369	425
Black	154,576 (5.67%)	87	173
Asian	116,583 (4.28%)	66	103
Native American	11,519 (0.42%)	6	18

Table 1. Racial and ethnic composition of Census Block Groups in the Denver Metro area

Residential parcels: We retrieved GIS layers of land parcels for each county separately, and merged them into a GIS layer for use as ancillary information in dasymetric mapping. Specifically, we retrieved City and County of Denver's parcels from the Denver Open Data Catalog (City and County of Denver, 2020), Adams county parcels from its GIS department website (Adams County GIS, 2020), and for the other four countries in the study area, from each county's entry in the Colorado Information Marketplace (Duran, 2021). Each dataset had its own unique attribute values for recording land use. We processed each county's dataset individually to subset to only residential parcels, converted the resulting polygons of residential parcels into Boolean rasters with 10m spatial resolution, and then, mosaiced the counties' Boolean rasters together to generate a single Boolean raster indicating the residential and non-residential pixels in the study area, with each pixel set to 1 for residential and 0 for non-residential areas.

Street networks: We used Esri's live street network dataset hosted on https://logistics.arcgis.com/ and set our analysis time for late January 2021, as explained in the Section 2.3 below.

2.2 Intelligent dasymetric mapping

Census Block Groups are the smallest geographic units for which the Census Bureau publishes sample data. CBGs typically contain between 3000 to 6000 people. Nevertheless, the boundaries of CBGs can cover geographically vast areas. For instance, the largest of the 1768 CBGs in our study area spans 1747km^2 and contains a population of 3208. The mean and standard deviation for areas of CBG are 5.55 km^2 and 51.03 km^2 respectively, and 1587 and 936 for population counts of CBGs in the study area. While the population counts are more homogeneous across CBGs, the areas vary significantly due to several sparsely populated CBGs in the study area, e.g., the Rocky Mountain Arsenal National Wildlife Refuge, Cherry Creek State Park, airports, and mountainous regions of the Front Rage towards the west.

Using aggregated CBG populations for analyzing accessibility may lead to unreliable results, since CBG aggregation assumes that population is evenly distributed within CBGs. Therefore, we used Intelligent Dasymetric Mapping (IDM) to redistribute the CBG populations to

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the residential parcels in the study area (Mennis et al., 2006). By redistributing population into residential parcels, which automatically leads to the exclusion of uninhabitable areas such as open water, high slopes, parks, and industrial zones, we focus our analysis of *spatial accessibility* of testing and vaccination sites *from* the resident's home location, i.e., same locations where population characteristics such as race and ethnicity were measured and published by the Census Bureau (as opposed to business locations, for instance). To implement IDM, we used the Dasymetric Toolbox developed and published by the Environmental Protection Agency (EPA) for use within Esri's ArcGIS Desktop environment (Pickard et al., 2015).

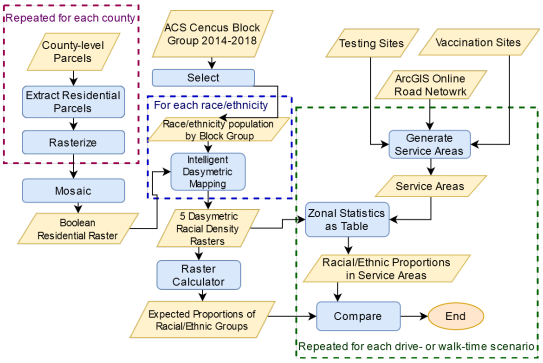

Figure 1: Overview of GIS operations for analyzing accessibility of vaccination and testing sites

We used the six central counties' CBG population as source population distribution to the IDM process, and residential parcels as ancillary information for redistributing population. The areas not covered by residential parcels provide the "preset to zero" areas for population density in our redistributed population output. Following the detailed steps in the EPA IDM toolbox, which is an implementation of IDM described in (Mennis, 2009), first, we calculated the inhabited population area for each source unit by subtracting the area of nonresidential locations from the total area. Then, for the residential class (whose population is not preset to zero), we calculated the representative population density as the sum of total population divided by the sum of total inhabited area. For each residential parcel, we calculated a population estimate by multiplying the representative population density by the area of the parcel. To maintain pycnophylactic integrity for each population unit, we derived the sum of the population estimates and calculated a *distribution ratio* equal to output unit (residential parcel) population estimate divided by the total estimated population for the specified population unit (CBG). Finally, we multiplied the output unit's distribution ratio by the initial population of the source unit to determine the final population estimate. The EPA IDM toolbox wizard allows a step-by-step replication of this process, with open source code built with Esri ArcGIS functions.

IDM generates a floating-point output raster of revised population density, which we then used in counting populations of different racial/ethnic groups falling within service areas of testing or vaccination sites. We ran the IDM process for population counts of different races/ethnicity populations in the study area, namely, White, Black, Hispanic, Asian, and Native American, resulting in five redistributed population density rasters, one for each race/ethnicity. We confirmed the equality of total populations before and after the dasymetric redistribution as quality control. Figure 2 shows the original CBG aggregates (before IDM) as well as redistributed Black populations in downtown Denver, as a result of IDM using residential parcels.

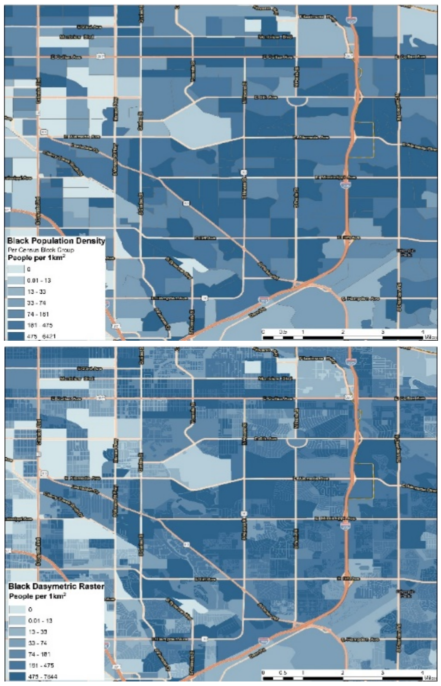

Figure 2: Top: Black/African American population in census block groups in downtown Denver. Bottom: Redistributed Black population using dasymetric mapping with residential parcels as ancillary information in the same area.

2.3 Generating testing and vaccination service areas

Service area is a common GIS terminology, referring to the region encompassing street networks around facilities (e.g., testing or vaccination sites) that can be accessed within a given distance or travel-time. For example, the 10-minute drive-time total service area of testing sites includes the regions where residents are able to reach a testing site by a maximum of 10 minutes of driving. Service areas are commonly used to measure accessibility in various domains, including health care access (Luo et al., 2003; Yang et al., 2006).

In addition to the location of facilities (e.g., testing sites), creation of service areas requires topologically correct and attribute-rich road network datasets. For instance, the network nodes should properly indicate passable junctions or bridges; road speed limits should be recorded for each segment; and the barriers, one-way streets or streets without sidewalks are marked in the dataset. We used Esri's *Ready To Use* service (Esri, 2021) to access the high-quality and frequently updated road network dataset hosted by ArcGIS Online at https://logistics.arcgis.com/ for generating the service areas.

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It is worth noting that while this is a commercial service, we (and many other institutes) have free access to ArcGIS Online Geoprocessing services through education and research licensing. Through the use of this commercial service, the service areas generated in this study incorporate realistic constraints in travel modes, including barriers, speed limits, usual traffic conditions, street directions and potential seasonal constructions.

We adopted maximum travel-time (for both walking and driving modes) as the cut-off for determining service areas. In other words, we specified travel-time (from residence), which is a function of distance and speed of movement, as the measure for accessibility of testing or vaccination sites. Using distance alone as a measure of accessibility can be misleading, especially for driving modes, e.g., a scenario where a vaccination site is accessible via a high-speed freeway within a short period of time. For walk-time service areas, we specified a speed of 5 km/hr on all roads and paths. For drive-time service areas, the typical weekday traffic conditions and speed limits in January 2021 were assumed.

Our analysis assumes that those seeking testing or vaccination are traveling from their place of residence, and not from a workplace or elsewhere. Also, race/ethnicity data are sampled at the place of residence by ACS, and our research question is centered on the accessibility of sites by different racial and ethnic groups.

We generated service areas separately for vaccination and testing sites, and for each, a separate set of total service areas for 10- and 20-minute walk-time (at 5km/hr) scenarios, as well as, 5-, 10- and 15-minute drive-time (at the speed limit) scenarios to generate non-overlapping service areas (Figures 3).

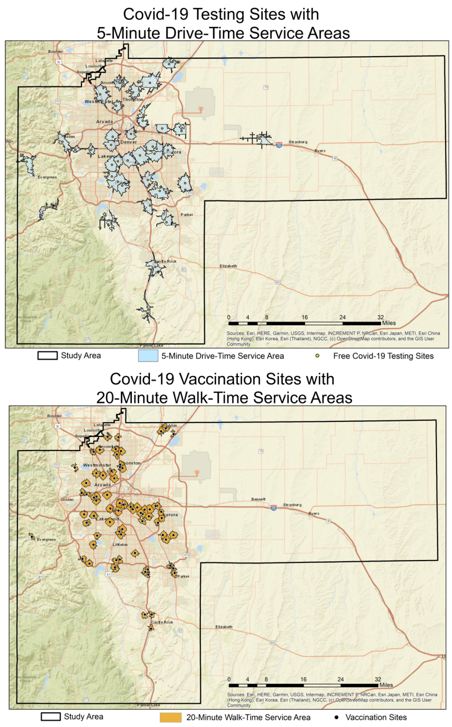

Figure 3. Service areas of testing and vaccination sites for a subset of scenarios with different travel modes and travel-time thresholds.

2.4 Calculating the racial and ethnic composition of service areas

As explained in the previous section, we applied 5 (2 walk-time and 3 drive-time) thresholds to create service areas of testing and vaccination sites for each travel mode and threshold separately. We then calculated the population proportion of each race/ethnicity in the service areas of each scenario. For this purpose, we calculated zonal statistics on each race/ethnicity population dasymetric raster with input zones defined by the specific scenario's service areas. The output zonal statistics tables contained the total *count* of residents from each racial/ethnic group within the scenario's service areas, from which we derived the total *proportions* of each race/ethnicity in each scenario's service areas. Finally, we compared these proportions with the proportions of the selected five races/ethnicities (White, Black, Hispanic, Asian and Native American) in the entire study area, which we refer to as the expected proportions. The rationale is that the overall proportions of racial groups in the study area (Denver) should be reflected in the proportions observed across the service areas in each scenario. This comparison allows us to investigate our research question, i.e., whether minority populations are underrepresented in the testing and vaccination service areas during a crucial time of vaccination role out and increase in testing sites.

3. Results

As is evident in Figure 3, our incremental expansion of service areas with both walking and driving modes allows for the characterization of accessibility in places more proximate to the sites as well as the overall study area. Table 2 lists the overall population percentages within the *total* service areas specified by increasing the travel-time threshold. *Total* service areas consist of *individual* service areas each established around an individual site. It is worth noting again that the testing sites used in these analyses are only the ones listed as free or having no out-of-pocket cost after insurance. Only 2% and 9.5% of the study area population has 10- and 20-minute walking access to these testing sites, respectively, while 26% can access a site by a maximum of a 5-minute drive. The percentage with access to a testing site increases to 94.9% for a 20-minute drive-time.

Travel mode		**Walk-time service areas**		**Drive-time service areas**		
Threshold		***0-10 minutes***	***0-20 minutes***	***0-5 minutes***	***0-10 minutes***	***0-20 minutes***
Population in testing total service areas	**count**	**56,505**	**258,208**	**712,576**	**2,177,419**	**2,587,969**
	% of Denver metro area	**2.07%**	**9.47%**	**26.13%**	**79.85%**	**94.90%**
Population in vaccination total service areas	**count**	**142,937**	**537,606**	**1,263,453**	**2,344,253**	**2,596,696**
	% of Denver metro area	**5.24%**	**19.71%**	**46.33%**	**85.97%**	**95.22%**

Table 2. Coverage of total service areas in different scenarios

As Table 3 and Figure 4 indicate, Black, Hispanic, and Native American populations are not underrepresented in the testing *total* service areas, as compared to the overall proportion of Black, Hispanic, or Native American populations, in the Denver metro area. Figure 4 shows the proportions observed in total service areas divided by the proportions observed in the study area (i.e., expected proportions), and Table 3 shows the population counts

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and proportions for each scenario. Most notably, the 10- and 20-minute walk-time total service areas encompass considerably larger proportions of Black and Hispanic populations than expected in the entire metro area. Asian populations are slightly underrepresented in 10- and 20-minute walk time total service areas, however, they are slightly overrepresented in all drive-time total service areas. As elaborated on in the Discussion, drive-time testing service areas might provide more reliable measures of accessibility, since some sites limit testing to drive-through settings. Our data does not contain attributes on whether a site is drive-through only.

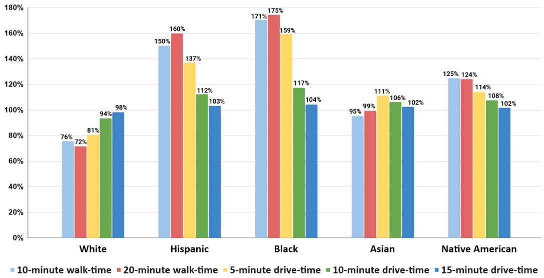

Figure 4. Proportions of racial and ethnic groups in the total service areas of sites offering free or no out-of-pocket cost COVID-19 testing, against (i.e., divided by) the expected (reference) proportions in Denver in January 2021.

Service Area Designation	White		Hispanic		Black		Asian		Native American	
	population count	*% of area population*	*population count*	*% of area population*	*population count*	*% of area population*	*population count*	*% of area population*	*population count*	*% of area population*
10-minute walk-time	28,125	49.77%	20,322	35.96%	5,461	9.67%	2,299	4.07%	298	0.53%
20-minute walk-time	121,520	47.06%	98,827	38.27%	25,544	9.89%	10,961	4.24%	1,355	0.52%
5-minute drive-time	377,416	52.96%	233,446	32.76%	64,387	9.04%	33,893	4.76%	3,435	0.48%
10-minute drive-time	1,337,885	61.44%	585,824	26.90%	144,748	6.65%	99,062	4.55%	9,900	0.45%
15-minute drive-time	1,670,747	64.56%	639,765	24.72%	152,970	5.91%	113,356	4.38%	11,130	0.43%
Overall Study Area	1,791,572	65.70%	652,657	23.93%	154,576	5.67%	116,583	4.28%	11,519	0.42%

Table 3. The proportion of racial and ethnic groups in the total service areas of sites offering COVID-19 testing with no out-of-pocket cost and the expected proportion as observed in the study area in January 2021.

The White population is consistently underrepresented in the total service areas of testing sites (Table 3 and Figure 4). However, this is largely due to the fact that the population in the Denver suburbs, where there are fewer testing sites, is disproportionately White (Connor et al., 2020).

Figure 5 shows the racial/ethnic proportions in *individual* testing service areas for different drive-time scenarios. The proportion of racial/ethnic groups in the *individual* testing service areas (established around *each* testing site) is also shaped by the lingering history of racial segregation in Denver (Connor et al., 2020; Wingerter, 2019). It is no surprise that some individual testing service areas serve predominantly Black, White, or Hispanic populations. White populations are overrepresented in more than half of the testing individual service areas in each scenario, however Black, Asian, and Native American populations are underrepresented in more than half of the individual service areas (Figure 5). In other words, a few testing sites cover largely Black or Hispanic populations, compensating for underrepresentation in other individual service areas, so that as a whole, Black and Hispanic populations are overrepresented in the *total* service areas (Figure 4 and Table 3).

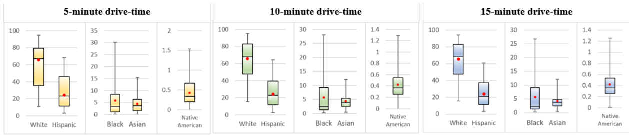

Figure 5: The proportion of racial/ethnic groups in the individual drive-time service areas of testing sites for different scenarios (a) 5-minute (b)10-minute and (c) 15-minute. Red dots show expected proportions. In all scenarios, the Black populations are underrepresented in more than half of individual service areas. However, a minority of individual sites' service areas serve disproportionately higher numbers of Black populations, as observed by the longer upper whiskers for respective boxplots.

As germane to our research question, racial and ethnic minority populations are overrepresented in the total drive-time service areas of testing sites compared to the overall racial/ethnic population proportions within the bounds of our study area. The testing sites are located such that the shorter the travel-time threshold is, the higher the observed proportions of Black and Hispanic populations covered in the total service areas are. Since our data source does not include the service capacity of sites, we are unable to perform catchment-area analysis reflecting the service capacity to population groups.

Looking at the proportions in vaccination total service areas (Figure 6 and Table 4), we observe a relatively similar pattern to the testing sites, albeit the proportions overall are closer to the expected proportions, given the better coverage provided by a total of 81 designated vaccination sites in the area (in contrast to the 38 testing sites with no out-of-pocket cost). White populations are slightly underrepresented in the total service areas, and Asian populations are underrepresented in the 10- and 20-minute walk-time and 5-minute drive time total service areas. Still, the differences are small (less than 6% difference between the expected proportion and the proportion of Asian population in the 10-minute walk-time service area). Additionally, Asian populations are overrepresented in 10- and 15-minute drive-time service areas, providing reasonable, albeit not spatial ideal, access. Black populations are slightly underrepresented in the 10-minute drive-time service area, however, they are overrepresented in all other thresholds, indicating equitable spatial access. With these exceptions stated, overall, ethnic and racial minority populations are not underrepresented in the vaccination total service areas in metro Denver, provided that all these vaccination sites are in fact operational with sufficient capacity (we did not have data to confirm this).

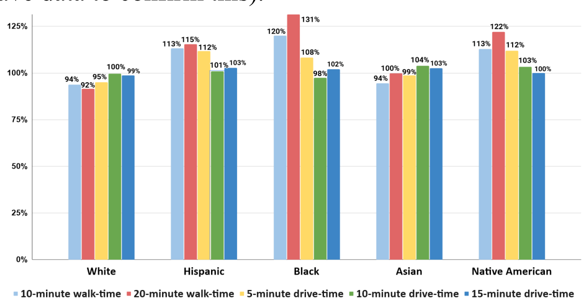

Figure 6. Proportions of racial and ethnic groups in the total service areas of COVID-19 vaccination sites against (i.e.,

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divided by) the expected overall proportions in the Denver metro area.

Service Area Designation	White		Hispanic		Black		Asian		Native American	
	population count	*% of area population*	*population count*	*% of area population*	*population count*	*% of area population*	*population count*	*% of area population*	*population count*	*% of area population*
10-minute walk-time	88,005	61.57%	38,756	27.11%	9,721	6.80%	5,773	4.04%	682	0.48%
20-minute walk-time	323,417	60.16%	148,438	27.61%	40,047	7.45%	22,932	4.27%	2,773	0.52%
5-minute drive-time	788,842	62.44%	337,859	26.74%	77,491	6.13%	53,290	4.22%	5,971	0.47%
10-minute drive-time	1,533,935	65.43%	566,455	24.16%	129,571	5.53%	104,057	4.44%	10,235	0.44%
15-minute drive-time	1,682,986	64.81%	638,752	24.60%	150,158	5.78%	113,834	4.38%	10,966	0.42%
Overall Study Area	1,791,572	65.70%	652,657	23.93%	154,576	5.67%	116,583	4.28%	11,519	0.42%

Table 4. The proportion of racial and ethnic groups in the total service areas of COVID-19 vaccination sites

We must note that in late January 2021, the city and county of Denver (one of the six counties constituting the Denver metropolitan area) advertised mobile testing to those unable to travel to a facility and experiencing symptoms ("Denver Testing Resources," 2021). We were unable to obtain data on the utilization of these services, and to the best of our knowledge, other counties in the study area did not offer this service.

4. Discussion

Our analysis showed that racial/ethnic minority populations were not underrepresented in the drive-time spatially accessible *total* service areas of testing and vaccination sites in the Denver metro area in January 2021, a period during which testing became more accessible and vaccines started rolling out. As discussed in the introduction, studies conducted in the earlier phases of the pandemic had suggested lower rates of testing and lower spatial accessibility of testing sites for racial/ethnic minority populations in U.S. cities (Kim et al., 2020; Lieberman-Cribbin et al., 2020). While spatial access to testing in the Denver metro area might have been addressed by January 2021 as observed in our results, people of a racial/ethnic minority were far less likely to receive the COVID-19 vaccine as of the same time in Colorado (Dukakis, 2021). This might also have been partly due to lack of trust in the vaccine as well. In a survey of adults in the U.S. in January 2021, White adults (53%) were more likely than African American/Black (35%) and Latino (42%) adults to say that they would want to get vaccinated "as soon as possible" (KFF, 2021). Conversely, Black (43%) and Hispanic (37%) adults were more likely than White adults (26%) to say that they want to "wait and see" before getting vaccinated. Therefore, community outreach, education on the effectiveness of the vaccine, and establishing trust are crucial to encourage vaccination.

Our study has important limitations. One is our lack of data on the capacity of testing or vaccination sites, which was not provided by the health or GIS departments of the counties. It is conceivable to derive the capacity of hospitals in health care accessibility studies through proxies such as number of beds, occupation rates or number of staff. However, in the case of the COVID-19 pandemic, with testing and vaccination sites set up temporarily with little planning or site-specific data records, data were not available on testing or vaccination capacity by *site* at the time. We observed that minority populations were underrepresented in the majority of testing sites' *individual* service areas (Figure 5), however, some individual sites served higher proportions of racial/ethnic minority populations, such that they were overrepresented in the *total* service areas of the sites (Figure 4 and Table 3). This makes the wait-time and capacity of a testing site all the more relevant, especially that for instance, a few testing sites cover largely Black populations, compensating for underrepresentation in other service areas. Another limitation is that we assumed that appointments and vaccines were equitably available at different testing/vaccination sites, and that the populations across different racial/ethnic groups fell relatively evenly within the designated age-categories who were permitted to receive the vaccine at that time (with older adults having priority).

Another limiting factor was differentiation of drive-through sites. COVID-19 is a contagious disease; therefore, to reduce the exposure of healthcare workers and patients, many testing sites operate in drive-through settings only. Some testing sites switch between normal operations and drive-through, based on the weather. Therefore, the drive-time service areas generated in this study provide more reliable proxies into understanding the spatial accessibility of testing and vaccination sites. The confounding factor, however, is that lower income residents are less likely to own a car, and therefore, could be deprived of testing, even if the sites are walk-in accessible. Our study did not measure access through public transit routes, which is another limitation.

Nevertheless, distance can still be a major obstacle to accessing the sites, especially when taking public transport potentially carries risks of exposure to the virus, and therefore, may prevent individuals from seeking testing or vaccination. Therefore, we also incorporated the 10- and 20- minute walk-time service areas in our analyses to investigate the demographic composition of areas proximate to the sites. The only racial minority group underrepresented in the walk-time total service areas (of vaccination or testing sites) were Asian populations, even though they were over-represented in the corresponding drive-time total service areas.

From a methodological point of view, the potential of dasymetric mapping for accessibility studies is worth discussing. Dasymetric mapping creates a more accurate representation of who lives within a service area, especially for spatial units. The redistribution is also important for reliable results in walk-time scenarios. In this study, we used residential land parcels as ancillary information to redistribute the population. The areas not covered by residential parcels provide the "preset to zero" areas for population density in our redistributed population output, i.e., our *Boolean* dasymetric mapping is a case of areal interpolation with certain places being inhabited and other places uninhabited, as opposed to more sophisticated Intelligent Dasymetric Mapping (IDM) approaches that take also into account the varying population densities in several sampled land use classes. IDM is especially useful for large study areas encompassing urban, suburban, rural (developed) and uninhabited areas, which was not the case in our study.

Future research can utilize the National Land Cover Dataset (NLCD) as ancillary information to take full advantage of such varying densities in IDM. NLCD, which is derived from satellite imagery and has a spatial resolution of 30-meters, is openly and readily available for the entire United States from the USGS website. To take full advantage of IDM, NLCD and Parcel GIS layers can be simultaneously used as ancillary information, allowing the IDM process to empirically derive the density of populations in different NLCD developed classes, such as the *Developed Open Space, Developed Low-, Medium-* and *High-intensity* classes as ancillary information in redistributing population (Ruther et al., 2015). Residential parcels help limit the developed spaces further into *residential* developed places for population redistribution, and more importantly, compensate for NLCD's known accuracy issues in suburban and rural areas (Zoraghein et al., 2016).

Residential parcels, generated by cadaster and ground surveys, provide direct and more precise observations of residential lands, especially in suburban and rural areas (in contrast to satellite imagery). However, parcel datasets in the US are usually less accessible, and only available upon request from each county's GIS department separately, due to historical data-sharing practices. Some counties have made their parcel datasets available to the public, including some counties in our study area. In lieu of parcel data, other datasets can be used in future research as ancillary information for dasymetric mapping, including Microsoft's Building Footprint dataset (Microsoft, 2018), which if used in conjunction with residential parcels, allows for an even more accurate picture of population redistribution. However, more scripting and custom implementation of the IDM toolboxes would be necessary to allow for detailed combinatorial use as ancillary data.

5. Conclusion

Incidence of COVID-19 and its disease burden disproportionately impacted racial and ethnic minority populations in the U.S., and in Denver, Colorado. Systemic inequalities need to be addressed by public health systems and social services to mitigate these disparities. Focusing on the Denver metropolitan area in January 2021, a period during which public vaccination was rolling out and testing was becoming more readily available, we analyzed the demographic composition of testing and vaccination total service areas generated using several maximum drive- and walk-time thresholds. We observed that racial/ethnic minority populations were not underrepresented in the total service areas, indicating equitable spatial access. Data on the capacity of testing and vaccination sites were not available, limiting the conclusions of this study based on the use of maximum travel-time as a measure of spatial accessibility. We note that these results only apply to metropolitan Denver, and only indicate reasonable spatial access to testing and vaccination sites during the current pandemic. Further work is needed to evaluate and address differential access to effective treatment and vaccination in other locations.

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