AN ASSESSMENT OF REGIONAL TRANSIT ACCESSIBILITY IN THE SAN FRANCISCO BAY AREA USING URBANACCESS

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ABSTRACT
Accessibility is an important metric in regional transportation and land use planning and as a component in equity analyses. Accessibility in the San Francisco Bay Area is characterized using a new multi-modal network accessibility tool, UrbanAccess. Accessibility is measured using open pedestrian and operational schedule transit network data at the Census block level across a large metropolitan extent. Additionally, a framework to assess changes in accessibility resulting from alternative transit network structures is developed. Results indicate the Bay Area has relatively high levels of accessibility to jobs by walking and transit. However, accessibility varies significantly by annual household income and geography. Disparities in job accessibility were most pronounced between Census blocks that were in poverty or not in poverty.

Keywords: Accessibility, Transit, Pedestrian, Network, Open Source, Regional Planning, GTFS, OpenStreetMap, San Francisco Bay Area, UrbanAccess

INTRODUCTION

Within regional and transportation planning and geography, accessibility has long been an important topic *(1)*. The quality of a transportation system and the relative connectivity between land uses can be measured objectively using accessibility metrics that characterize the ease of access to destinations or opportunity sites. The structure and quality of the transportation network and the spatial distribution and attributes of land use can have important implications on access to jobs and housing and subsequently impact housing affordability, quality of life, social equity, and the environment *(2–8)*. Access to quality transportation infrastructure and services may be distributed unequally across space and disproportionately serve different sectors of the population varying by socioeconomics and demographics *(9–12)*. In particular, job accessibility has been found to be unequal across industry and geography. On average in the United States, only 30 percent of jobs in a metropolitan area are accessible within a 90 minute transit commute time with uneven access between low- and middle-skill industries and high-skill industries *(13)*.

The analysis and understanding of regional transit accessibility and system performance is important for metropolitan planning organizations (MPOs) to efficiently and equitably allocate resources and regional transit agencies to assess transportation service performance, connectivity, and equity *(14, 15)*. Analyzing accessibility and transit system performance at the regional scale allows for a system level and multi-scale perspective to understand trends in accessibility and service that may be obscured at a municipal or transit agency scale.

The objective of this research is to characterize accessibility in the San Francisco Bay Area at the metropolitan extent using an integrated pedestrian and transit network. Accessibility is calculated at the Census block level and differences in accessibility by geography, employment, and select socioeconomic characteristics are identified. In addition, a framework to assess changes in accessibility resulting from alternative transit network structures and service provision levels is developed to analyze hypothetical changes to the transit network in support of transit service scenario planning.

LITERATURE REVIEW

Accessibility in Regional Planning and Modeling

Transit accessibility measures have been used to examine a diversity of topics ranging from assessments of the equity of transit service quality and access across socioeconomic groups *(6, 9)*; to identify underserved neighborhoods *(16)*; to measure the degree of auto-centricity *(17)*; to aid in transit service planning *(18)*; as components in hedonic models of house prices *(19)* and pedestrian accessibility indices *(20)*; and to measure transit system demand and performance *(21)*.

MPOs typically use accessibility metrics as components in travel demand, location, and mode choice models to project population and employment growth and transportation infrastructure and housing demand *(22–24)*. Accessibility metrics aid in the characterization of the regional housing and job market as well as individual travel behavior and help to inform long range regional transportation plans, transportation improvement programs, and regional housing needs. These plans help guide regional planning policy and transportation infrastructure expenditures. Transit accessibility metrics are also used by MPOs to inform equity analyses, measuring differences between transportation infrastructure improvements, and to support scenario planning. While accessibility metrics are commonly used at the regional level by MPOs, accessibility metrics for non-single occupancy automobile modes such as transit tend to be inadequately represented in land use and transportation models *(25)*.

Additionally, scholars have identified the need to improve the methods used in MPO equity analyses and increase the transparency in the regional transportation planning process *(26–29)*. Through Title VI of the 1964 Civil Rights Act and Executive Order 12898, MPOs are federally required to consider the impact of their decisions and transportation infrastructure and policy on low income and minority communities *(30)*. Although there are exceptions, MPO equity analyses have been found to lack the scope and methods required to adequately measure impacts *(27)*. The technical and analytical methods used in practice at MPOs have not kept pace with the evolving understanding of the environment and complex systems and the growing federal, state, and regional goals and requirements placed on MPOs *(28)*. In some states, such as California with state legislation enacted within the last 10 years such as Assembly Bill 32 (AB 32) California Global Warming Solutions Act, Senate Bill 375 (SB 375) Sustainable Communities and Climate Protection Act, and Senate Bill 743 (SB 743) reforming the California Environmental Quality Act, state law has substantially expanded the scope of land use, transportation, and environmental planning goals.

STUDY AREA

The study area is the San Francisco Bay Area MPO jurisdiction in California and includes the counties of Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Sonoma, Solano, and Santa Clara. The Metropolitan Transportation Commission (MTC) MPO and the Association of Bay Area Governments (ABAG) Council of Governments are responsible for regional planning in the Bay Area. In 2015, the Bay Area was home to 7.5 million people and 3.8 million jobs, according to the California Department of Finance and California Employment Development Department respectively. The Bay Area is a geographically diverse region with a highly fragmented governance structure made up of 9 counties and 101 cities covering 7,179 square miles. The region is among the nation’s most expensive housing markets which places substantial pressure on the regional transportation network to provide a balance between job access and housing affordability *(31, 32)*. These characteristics pose substantial challenges for the equitable, efficient, coordinated, and integrated provision of transit service across the region *(33)*.

According to the Federal Transit Administration’s (FTA) National Transit Database (NTD), there were an estimated 1.7 million weekday trips taken on public transit services in the Bay Area for fiscal year 2013-2014. 32 individual transit services are provided by 30 individual transit agencies and service providers. The Bay Area transportation network is structured as a hub and spoke system with the majority of service connecting major population centers to each other and to the center of the region to San Francisco and Oakland. San Jose and Santa Clara serve as another major hub with transit networks primarily serving the greater South Bay. Many transit services such as Bay Area Rapid Transit (BART), Caltrain, Amtrak’s Capital Corridor, Altamont Corridor Express (ACE), and the regional ferry system operate over multiple geographies outside of any one single county. The more urbanized and densely populated counties of San Francisco, Alameda, and Santa Clara have the largest and densest transit coverage in the region providing both regional and neighborhood transit access. The more sparsely populated suburban and rural counties of Napa, Marin, Sonoma, and Contra Costa have smaller transit coverages that operate a sparser network oriented to move people to and from major population centers.

DATA

Transit network

General Transit Feed Specification (GTFS) *(34)* transit schedule data was programmatically acquired and validated using UrbanAccess, a new open source tool. GTFS is a standard format for transit services to disseminate transit network information and consists of trip, stop, route, stop time, and in some cases fare information. These data are used to generate a transit network. In order to characterize all transit services in the Bay Area, GTFS data from multiple sources were used and include: 1) GTFS feeds located on the global and centralized GTFS Data Exchange repository *(35)*; 2) GTFS feeds hosted by individual transit service providers; and 3) GTFS feeds in the MTC's regional 511 GTFS feed database *(36)*.

36 individual feeds representing 29 individual administrative agencies were acquired which can be considered a compete and up to date representation of all fixed route transit services in the Bay Area as of October 2015 with the exception of small shuttle operators. In total, the GTFS feeds represent 23,662 stops and 73,198 trips with the majority of stops and trips active during the weekday (90% and 45% respectively) and peak period (96% and 51% respectively).

Pedestrian network

Pedestrian accessible street and path network data (e.g. paths, stairways, and roads that are not limited access highways) from OpenStreetMap (OSM) *(37)* were acquired to create the pedestrian network. Data from March 2016 were programmatically extracted from OSM using the Overpass application program interface *(38)*. OSM is a free, global, open source, and community edited database of geographic data.

Employment and socioeconomic accessibility variables

Accessibility is calculated at the Census block level using a cumulative accessibility metric that returns the sum of each variable's value at each block that is reachable within a given travel time threshold on the pedestrian and transit network. Employment is used as the main variable to operationalize accessibility and is considered a standard metric in the literature *(14)*. Supplemental population and socioeconomic characteristic variables are also used.

Employment data from 2011 representing counts of total jobs by industry sector (2-digit North American Industry Classification System (NAICS) code) are acquired from the US Census Longitudinal Employer-Household Dynamics (LEHD) at the block level. Socioeconomic data from 2010 are synthetically generated at the Census block level. Synthetic data are generated in order to use more detailed socioeconomic data that are not available at fine scale Census spatial units. The open source tool, SynthPop, is used to synthesize data from the 2009-2013 American Community Survey (ACS) estimate Public Use Microdata Sample at the Public Use Microdata Area level to the block group level using an iterative proportional updating method *(39)*. The resulting data are the observed full household counts at the block level with associated socioeconomic variables matching their block group level distributions. Population synthesis is common in activity-based microsimulation modeling and this study's method is used by the MTC for their modeling efforts.

The following variables are used to characterize accessibility and include block level: 1) total employment across all industry sectors; total employment for industry sectors with mean annual salaries 2) above; and 3) below the 2011 Bay Area regional median annual household income of $77,197 *(40)*; and 4) mean annual household income. LEHD industry sectors were categorized into either above or below the median annual household income based on each industry sector's US Bureau of Labor Statistics mean annual salary for the State of California in 2011. Industrial sectors above the median annual household income include the following sectors: information; finance and insurance; professional, scientific, and technical services; and management of companies and enterprises.

METHODOLOGY

Integrated transit and pedestrian network

UrbanAccess is used to create the integrated transit and pedestrian graph network. The GTFS and OSM data are used to create a travel time weighted network graph comprised of nodes (e.g. stations, stops, or intersections) and edges (e.g. streets or transit right of way that connect the nodes) representing a transit operational schedule at a particular time of day. Weights are assigned to edges to represent travel impedance or cost in units of minutes. Census block centroids are used as the origins and destinations (ODs). Accessibility is calculated between the ODs over the weighted transit and pedestrian network and is compared across the employment and socioeconomic variables.

Transit network nodes and edges

The transit network is a time dependent graph comprised of nodes (e.g. transit stations and stops) and edges weighted by the transit vehicle travel time between nodes in the operational schedule. GTFS data provides the benefit of an operational schedule that allows for specific time of day and day of week network calculations. Missing departure stop times are linearly interpolated between known stop times for a trip. Four distinct transit networks are created representing weekday service for three hour increments at the following four time periods:

1) AM Peak period: 7 a.m. to 10 a.m.;
2) Mid-day period: 11 a.m. to 2 p.m.;
3) PM Peak period: 4 p.m. to 7 p.m.; and
4) Late Night period: 12 a.m. to 3 a.m.

Based on 2006-2010 US Census Transportation Planning Package (CTPP) data, 68% of weekday commuters in the Bay Area travel from home to work between the hours of 6 a.m. and 10 a.m..

In-vehicle trip time for each trip stop pair is calculated by subtracting the departure times for each trip between each stop pair. The data are then transformed into a nodes and edges where nodes represent the coordinates of a transit station or stop. The edges represent the connections between these nodes in one direction weighted by the on-board transit vehicle travel time. The transit edge impedance assumes no additional dwell time, boarding and alighting time, or traffic congestion. GTFS schedules in some cases already account for such considerations, but not in all cases.

Pedestrian network nodes and edges

The pedestrian network is comprised of the three components: 1) pedestrian to transit; 2) transit to pedestrian; and 3) pedestrian to pedestrian networks. The pedestrian to transit and transit to pedestrian networks are one way networks that represent the connection between each transit node and its corresponding closest pedestrian nodes. The edges for all three of these networks are weighted by the pedestrian travel time it takes to traverse the connection at 3 MPH (4.8 KPH). Additional impedance calculations occur for the pedestrian to transit edge where the average headway for each route level stop for the designated time period in the GTFS data is added to the pedestrian travel time to represent the expected passenger wait time at each transit stop.

Alternative infrastructure AM Peak transit network

In addition to the four time period integrated transit and pedestrian networks, an alternative infrastructure AM Peak transit network was developed that represents a future scenario transit infrastructure network. The network represents the integrated AM Peak transit and pedestrian network with additional transit services in the Bay Area that are either currently under construction, fully or partially funded with construction pending, or are within the planning process. Figure 1a shows the AM Peak transit network with the names and edge locations of the 14 projects selected for the alternative network in red. Figure 1b provides an overview of the study area geography. Projects include: the BART Livermore, East Contra Costa, Berryessa, and San Jose-Santa Clara extensions, the Santa Clara Valley Transportation Authority's (VTA) El Camino Real and Alum Rock/Santa Clara Bus Rapid Transit (BRT), Alameda-Contra Costa Transit District's (AC Transit) International Boulevard BRT, Caltrain's Downtown Rail extension to the future San Francisco Transbay Transit Center, the San Francisco Municipal Transportation Agency's (SFMTA) Central Subway T Third line extension and Geary and Van Ness Avenue BRT, the Sonoma-Marin Area Rail Transit (SMART) commuter train, and the San Francisco Bay Area Water Emergency Transportation Authority's (WETA) ferry expansion to Richmond, Berkeley, and Treasure Island.

Node coordinates were digitized using each project's published stop locations. Connecting edge weights for each project were initialized as the Euclidian distance between each node pair. Transit to transit edges were weighted using the measured or proposed average transit vehicle speeds for the corresponding transit service provider to generate estimated travel time. Pedestrian to transit network connector edges were weighted using the corresponding transit service provider's peak hour headways estimated for the proposed project or from similar current transit services. These new nodes and edges were then connected to the current integrated AM Peak transit and pedestrian network by linking extension projects to their respective originating transit nodes and new projects directly to the pedestrian network. The alternative AM Peak transit network assumes the current transit system will not be altered to accommodate the new transit services.

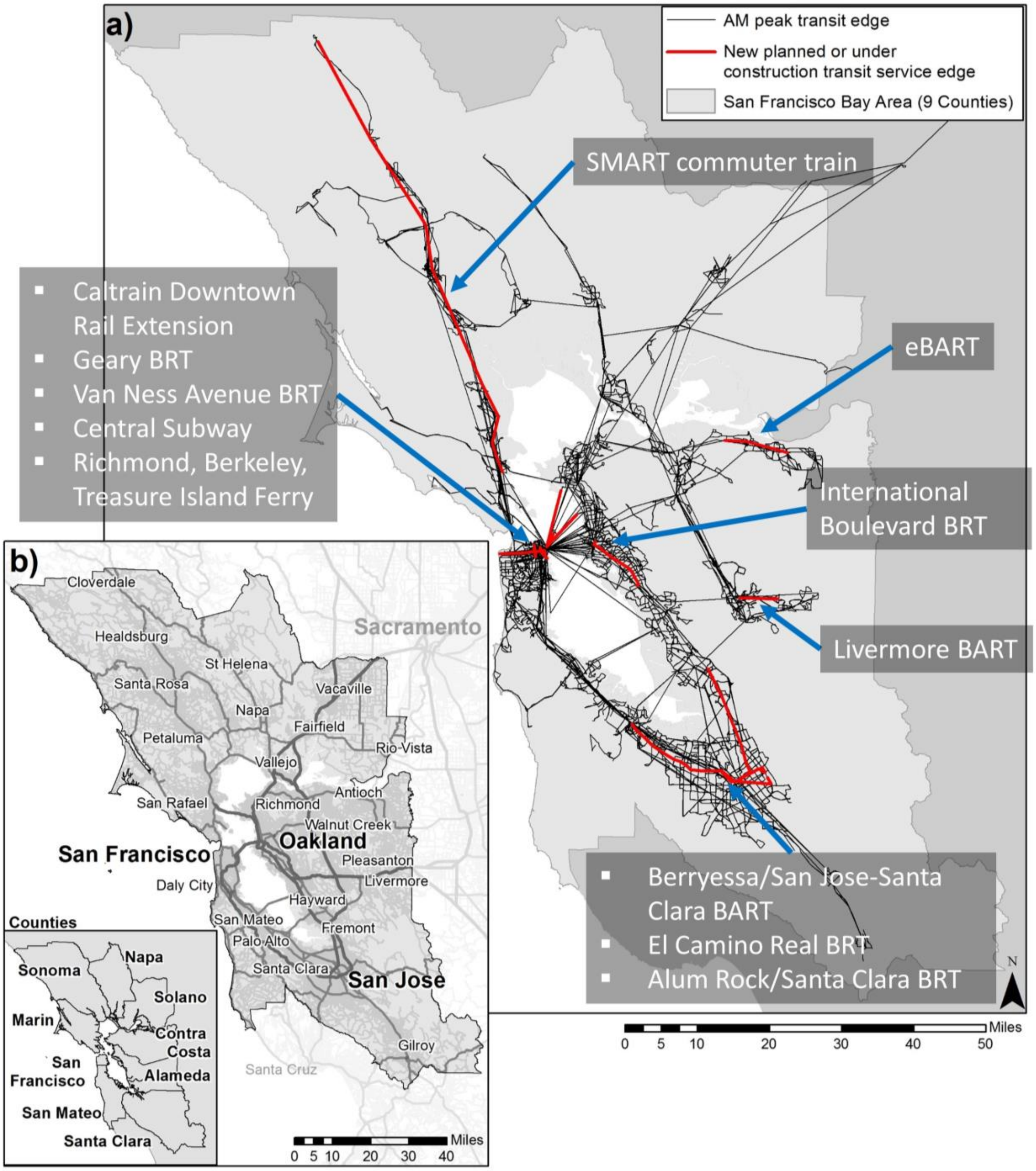

FIGURE 1 (a) San Francisco Bay Area alternative integrated pedestrian and transit network graph with planned or under construction future transit services operating during the AM Peak period; (b) Overview of the San Francisco Bay Area, CA study area geography noting major population centers and counties.

Note: BRT = Bus Rapid Transit; BART = San Francisco Bay Area Rapid Transit District; SMART = Sonoma-Marin Area Rail Transit; WETA = San Francisco Bay Area Water Emergency Transportation Authority; SFMTA = San Francisco Municipal Transportation Agency; AC Transit = Alameda-Contra Costa Transit District; VTA = Santa Clara Valley Transportation Authority.

Pandana and accessibility calculation

Transit accessibility was calculated using the open source Pandana *(41)* network analysis tool. Pandana requires: 1) a set of OD node coordinates (e.g. Census block centroids) for which accessibility will be computed between and can include variables, such as socioeconomic data, that can be aggregated; and 2) a network of nodes and weighted edges used for network routing. Pandana calculates the shortest path (e.g. lowest cost path) between ODs over a hierarchical network using the contraction hierarchies algorithm *(42)*. For more detailed description of Pandana see Foti and Waddell *(41)*.

Census block centroids from the 2010 synthetic employment and socioeconomic data were set as origins and destinations and the weighted integrated transit and pedestrian graph was set as the network. Accessibility was calculated using the summation cumulative opportunities function with a linear decay for the employment and socioeconomic variables. The linear decay function penalizes destinations further away from the origin. Accessibility was calculated using three travel time thresholds 20, 40, and 60 minutes. According to the 5-year ACS 2010-2014 estimates the average commute time to work in the Bay Area is 30 minutes (28 for drive alone and 50 minutes for transit).

RESULTS

Figure 2 shows the total number of jobs accessible within a 20, 40, and 60 minute commute for each of the four time periods. Yellow indicates low accessibility and dark blue indicates high accessibility. As expected, the AM Peak network provides the greatest coverage and access to jobs and the Late Night network provides the least access to jobs. There are very few locations outside of San Francisco, coastal Alameda County, and San Jose that are accessible to jobs within a 20 minute commute time. Accessibility for locations outside of the center of the Bay Area are greatest with commute times between 40 and 60 minutes (Figure 2).

Figure 3a shows one of the outputs from the accessibility analysis for the total number of jobs accessible by Census block within a 40 minute commute time during the AM Peak period. Figure 3b shows the standard deviation. As expected the dense urban centers have greater access to jobs particularly San Francisco and coastal Alameda County. San Mateo, Santa Clara, and Contra Costa Counties have the greatest accessibility to jobs along their main transportation arteries. Marin, Sonoma, Napa, and Solano Counties have the lowest accessibility to jobs. Accessibility within large urban areas can vary considerably in cities such as San Jose and San Francisco given the structure of the transit network (Figure 3).

Figure 3c and d show the difference in job access within a 60 minute commute between the AM Peak and AM Peak alternative networks. Overall, the intra-city transit improvements, such as the BRT improvements, resulted in an increase in job accessibility for areas directly adjacent to their routes particularly in west and north San Francisco and west Santa Clara and south San Mateo Counties. Inter-city or regional transportation improvements such as the BART and SMART projects resulted in the largest change in accessibility for areas outside the urban core in Sonoma, Solano, and Contra Costa Counties (Figure 3c). The greatest changes occurred in northern Sonoma County near Cloverdale and Healdsburg, Fairfield in Solano County, and western and eastern Contra Costa Counties (Figure 3d). The ferry expansion projects substantially increased job accessibility in and around the City of Richmond, west Berkeley, and San Francisco's Treasure Island (Figure 3c).

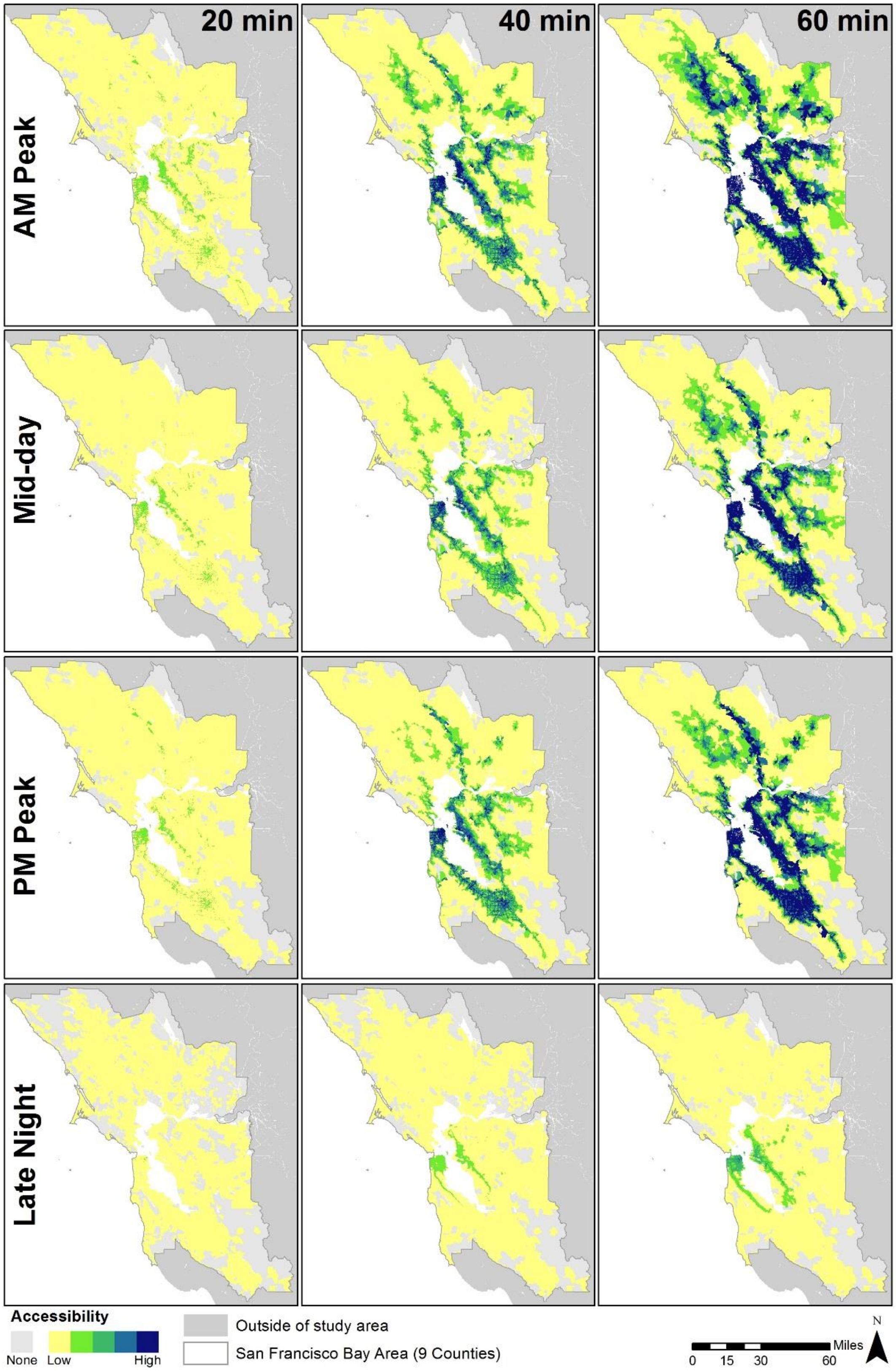

FIGURE 2 Total employment by Census block accessible within 20, 40, and 60 minute travel times for each of the four pedestrian and transit integrated network time periods.

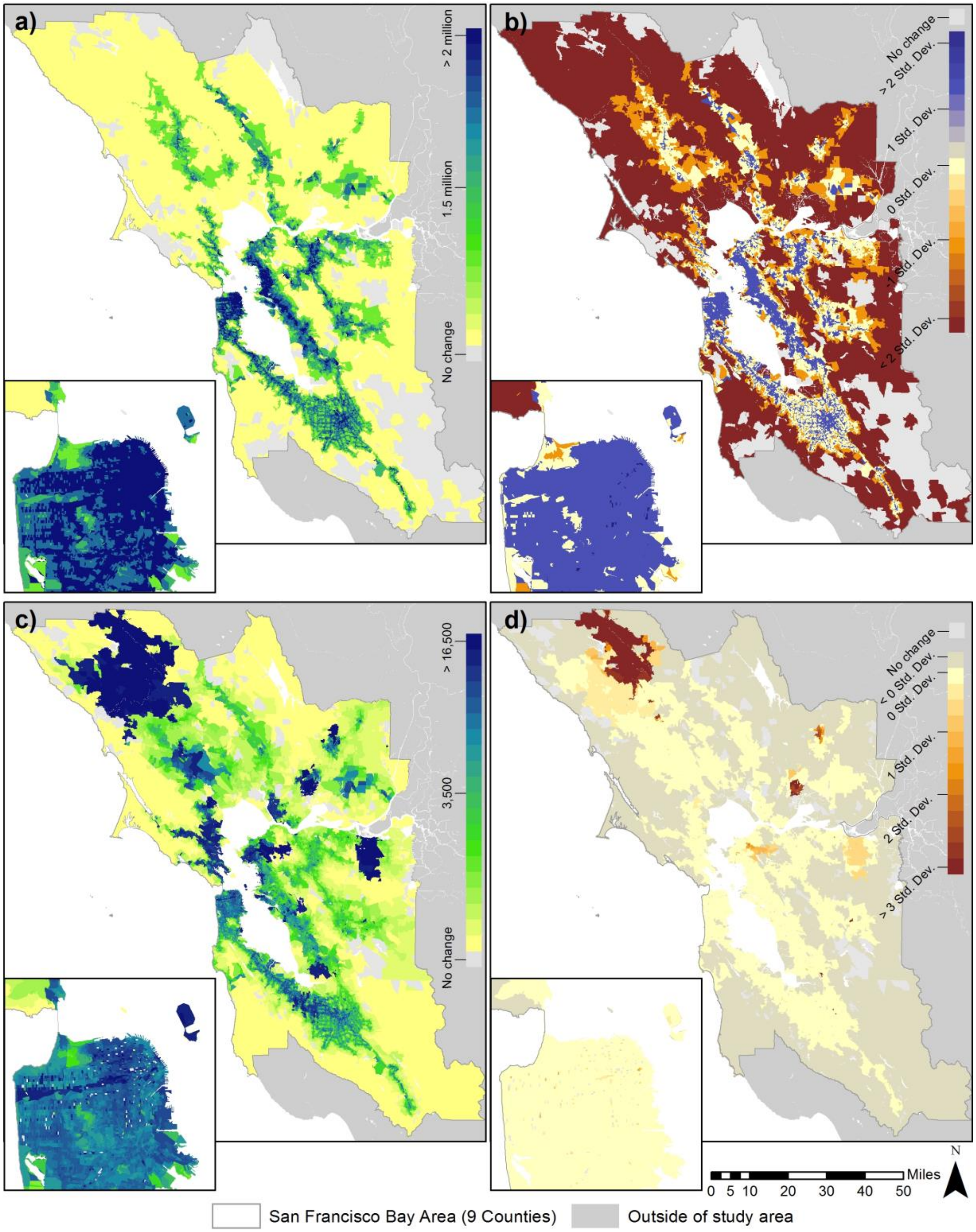

FIGURE 3 (a) Total employment by Census block accessible within a 40 minute travel time on the AM Peak pedestrian and transit integrated network; and (b) standard deviation; (c) Difference in total employment by Census block accessible within a 60 minute travel time between the AM Peak and AM Peak Alternative pedestrian and transit integrated networks; and (d) standard deviation of difference.

Table 1 shows the average number of jobs, jobs with mean annual wages above and below the regional median annual household income, and total population accessible in the Bay Area by 20, 40, and 60 minute commute times for each of the four networks and the AM Peak Alternative network. The AM Peak period has the highest average accessibility levels of the four time periods for all variables. The AM Peak network provides access to an average of 1,736,494 jobs (53.64% of the regional total) with 369,760 jobs with wages above and 1,337,337 jobs with wages below the regional median household income; and 3,299,648 population (48.95% of the regional total) within a 60 minute commute (Table 1). The AM Peak alternative network provides a small but measurable increase in aggregate accessibility in the Bay Area over the current AM Peak network. The greatest increase occurs for jobs with average annual wages below the regional median annual household income where, for example, the average accessibility increases by 9,233 jobs within a 60 minute commute (Table 1).

TABLE 1 Mean number of total jobs, total jobs with annual wages above and below the regional median annual household income, and total population accessible in the Bay Area by 20, 40, and 60 minute pedestrian and transit travel times by network operating time period and AM Peak Alternative network

		Mean number (% of regional total) accessible by travel time (Minutes)		
Network	**Variable**	**20**	**40**	**60**
AM Peak	Total jobs	324,710 (10.03%)	1,202,370 (37.14%)	1,736,494 (53.64%)
	Above regional median wage jobs	80,205 (12.07%)	263,598 (39.68%)	369,760 (55.66%)
	Below regional median wage jobs	238,900 (9.49%)	918,330 (36.47%)	1,337,337 (53.11%)
	Total population	428,593 (6.36%)	2,130,034 (31.60%)	3,299,648 (48.95%)
Mid-day	Total jobs	218,184 (6.74%)	942,264 (29.11%)	1,465,658 (45.28%)
	Above regional median wage jobs	52,159 (7.85%)	204,896 (30.84%)	311,488 (46.89%)
	Below regional median wage jobs	162,110 (6.44%)	721,009 (28.63%)	1,129,026 (44.83%)
	Total population	293,808 (4.36%)	1,654,389 (24.54%)	2,760,667 (40.95%)
PM Peak	Total jobs	233,587 (7.22%)	1,048,017 (32.37%)	1,593,283 (49.22%)
	Above regional median wage jobs	55,803 (8.40%)	226,323 (34.07%)	335,729 (50.54%)
	Below regional median wage jobs	173,690 (6.90%)	803,671 (31.91%)	1,230,362 (48.86%)
	Total population	316,815 (4.70%)	1,864,198 (27.65%)	3,035,076 (45.02%)
Late Night	Total jobs	44,293 (1.37%)	184,738 (5.71%)	350,855 (10.84%)
	Above regional median wage jobs	11,701 (1.76%)	43,788 (6.59%)	78,849 (11.87%)
	Below regional median wage jobs	31,752 (1.26%)	137,505 (5.46%)	265,669 (10.55%)
	Total population	50,881 (0.75%)	263,372 (3.91%)	556,913 (8.26%)
AM Peak Alternative	Total jobs	327,414 (10.11%)	1,211,605 (37.43%)	1,747,984 (54.0%)
	Above regional median wage jobs	80,588 (12.13%)	265,289 (39.93%)	371,752 (55.96%)
	Below regional median wage jobs	241,072 (9.57%)	925,612 (36.76%)	1,346,570 (53.47%)
	Total population	431,940 (6.41%)	2,145,987 (31.83%)	3,322,739 (49.29%)

Table 2 shows the average number of jobs accessible in the Bay Area for each of the four time periods and the AM Peak Alternative network categorized by Census block characteristics with blocks that are above and below the Bay Area median annual household income and Federal poverty level. Overall, Census blocks that have average annual household incomes above the regional median income have on average greater access to jobs compared to blocks with average incomes lower than the regional median income. This trend is greatest for the 40 and 60 minute travel times. Census blocks that have average annual household incomes below the Federal poverty level have on average less access to jobs compared to blocks with average incomes higher than the Federal poverty level (Table 2). The AM Peak Alternative network results in small increases in job accessibility over all categories, with a slightly higher increase in accessibility for blocks with average annual household incomes below the regional median income and the Federal poverty level (Table 2).

TABLE 2 Mean number of total jobs accessible in the Bay Area by 20, 40, and 60 minute pedestrian and transit travel times by network operating time period and AM Peak Alternative network for Census blocks above and below the Bay Area regional median annual household income and Federal poverty level

			Mean number of jobs (% of regional total) accessible by Census block category			
			Regional median annual household income		**Federal poverty level[1]**	
		Travel time (Minutes)	**Above**	**Below**	**Above**	**Below**
Network time period	**AM Peak**	20	305,174 (9.43%)	340,525 (10.52%)	335,614 (10.37%)	306,848 (9.48%)
		40	1,246,707 (38.51%)	1,166,475 (36.03%)	1,282,965 (39.63%)	1,070,344 (33.06%)
		60	1,811,741 (55.97%)	1,675,576 (51.76%)	1,838,612 (56.80%)	1,569,220 (48.47%)
	Mid-day	20	197,264 (6.09%)	235,121 (7.26%)	223,575 (6.91%)	209,369 (6.47%)
		40	974,574 (30.11%)	916,107 (28.30%)	1,007,892 (31.13%)	834,774 (25.79%)
		60	1,545,119 (47.73%)	1,401,327 (43.29%)	1,567,879 (48.43%)	1,298,242 (40.10%)
	PM Peak	20	217,353 (6.71%)	246,730 (7.62%)	238,803 (7.38%)	225,043 (6.95%)
		40	1,092,235 (33.74%)	1,012,220 (31.27%)	1,117,106 (34.51%)	934,831 (28.88%)
		60	1,680,051 (51.90%)	1,523,037 (47.05%)	1,694,354 (52.34%)	1,427,711 (44.10%)
	Late Night	20	39,016 (1.21%)	48,565 (1.50%)	44,420 (1.37%)	44,095 (1.36%)
		40	163,092 (5.04%)	202,263 (6.25%)	189,718 (5.86%)	176,613 (5.46%)
		60	326,908 (10.10%)	370,242 (11.44%)	363,736 (11.24%)	329,803 (10.19%)
	AM Peak Alternative	20	307,304 (9.49%)	343,695 (10.62%)	338,459 (10.46%)	309,322 (9.56%)
		40	1,253,058 (38.71%)	1,178,047 (36.39%)	1,291,813 (39.91%)	1,080,217 (33.37%)
		60	1,819,809 (56.22%)	1,689,837 (52.20%)	1,849,364 (57.13%)	1,581,922 (48.87%)

[1] 2011 ~$15,000 annual household income federal poverty threshold for a household of 2 with no children and under 65 years old

DISCUSSION

The results of the accessibility analysis help to inform future regional transportation and land use planning efforts in the Bay Area by providing a snapshot of accessibility to jobs using the current and planned future transit transportation system. On average for the AM Peak period, 10, 37, and 54 percent of all jobs in the region are accessible within respective 20, 40, and 60 minute pedestrian and transit travel times. The percentage of jobs accessible within a 40 and 60 minute travel time are higher than a previous study by Tomer et al. *(13)* that used a similar accessibility metric. Tomer et al. *(13)* assessed accessibility within a smaller metropolitan extent (e.g. metropolitan statistical area) using tract level employment and GTFS data. Tomer et al. *(13)* found 35 percent of jobs in the San Francisco-Oakland-Fremont metropolitan statistical area were accessible by transit within a 90 minute transit travel time and on average in the United States only 30 percent of jobs in a metropolitan statistical area are accessible within a 90 minute transit travel time *(13)*. In comparison to Tomer et al. *(13)*, the results of this study suggest the San Francisco Bay Area has higher than average regional job accessibility for the United States.

Only minor disparities in average regional job accessibility were found between jobs that have wages above and below the regional median annual household income. The most substantial finding is the disparity in job accessibility provided by the peak period transit and the non-peak period networks. These findings are not surprising given they are representative of common transit operational practices that prioritize service during the peak period commute hours, which hold the largest share of daily commuters. However, the lack of accessibility during off peak periods has implications for the 32 percent of Bay Area commuters that travel to work during weekday non-AM Peak hours, according to 2006-2010 US CTPP data. This is a sizable portion of the Bay Area's commuter population that are left with limited transit options to reach employment centers. This makes the automobile a more convenient mode for commuters who have access to vehicles, and exacerbates the commutes of those who have no other alternative other than to take transit.

Another important finding is the gap in job accessibility between households that are in poverty and those that are not. The difference in the average number of jobs accessible for households that live in Census blocks that are above or below the federal poverty level ranges from 7 to 9 percent for a 40 and 60 minute travel time respectively during the AM Peak period. When comparing the job accessibility results to areas identified by the MTC as having high concentrations of disadvantaged populations *(43)*, the central urban areas of the Bay Area have both the highest level of job accessibility and the largest concentrations of disadvantaged populations. However, a number of exceptions exist with the neighborhoods of East Palo Alto in Palo Alto, Hunters Point in San Francisco, and isolated neighborhoods in east Oakland, central Richmond, north San Jose, Antioch, and Vallejo having low job accessibility and high concentrations of disadvantaged populations. The gaps in the geography of job accessibility across the Bay Area suggest transit service could be improved to better serve neighborhoods that have high concentrations of disadvantaged populations that are more likely to be dependent on transit to access job markets than other populations *(44)*. Given that land use patterns and the transportation network are closely linked and interdependent on one another, planning for improvement in multi-modal accessibility should be closely coordinated with land use plans for local communities.

Accessibility to jobs varies substantially by geography in the Bay Area. Areas of greatest access within the 20 minute travel time are isolated to the dense urban centers of central San Francisco, Oakland, Berkeley, and San Jose and areas directly adjacent to the regional rail network (e.g. BART and Caltrain). Accessibility within a 40 and 60 minute travel time expands to most urbanized areas in the Bay Area, however suburban and rural areas are consistently left with lower levels of job accessibility than the central urban core of the Bay Area. This is representative of the concentrated housing and employment densities in the central Bay Area and the hub and spoke structure of the transit transportation network. The gaps identified in the geography of transit accessibility in the Bay Area have important implications on the regional jobs and housing balance. As the cost of housing continues to increase in the central and dense urban cores of the Bay Area, households looking for more affordable housing options will increasingly be looking to the urban fringe, far from job centers, and can face longer commute times and lower levels of job accessibility *(31, 32)*. The geographic disparities in transit accessibility can also create difficulties for regional planning initiatives attempting to comply with state environmental mandates to reduce greenhouse gas emissions under AB 32 and SB 375, as the automobile is the only means to access jobs in most suburban and rural areas.

The results of the alternative transit infrastructure network scenario analysis provide a demonstration of how the methodological framework presented in this study can be used to examine the impact of different transit improvements on accessibility. The selected 14 projects result in modest increases in job accessibility at the aggregate level. The extent of the change in access varied depending on the type of transit infrastructure improvement, its location, and connectivity to the regional transportation system. Intra-city transit improvements saw only localized improvements in access for areas directly adjacent to their routes. Inter-city or regional transportation improvements provided greater benefits in accessibility to suburban and rural areas outside the Bay Area urban core. The transit improvements planned in the northern Bay Area counties, particularly the SMART commuter rail system, resulted in the greatest improvement in regional accessibility. This suggests jurisdictions in this area are moving closer towards regional planning goals to reduce regional greenhouse gas emissions and are positioned to accommodate future dense housing and employment growth near transit in line with ABAG and MTC regional planning goals *(45)*. The alternative transit infrastructure network scenario could be further extended into practice by regional planning agencies by implementing a similar analysis but with a phased implementation of transit projects over time and connecting the derived accessibility metrics to a land use forecasting model to analyze future land use impacts.

CONCLUSION

This study leverages the new tool, UrbanAccess, to measure accessibility with an integrated pedestrian and transit network at a fine spatial scale over a large metropolitan extent using open source datasets. We do not propose this methodology as an alternative for travel demand models since we are not modeling modal choice or congestion patterns, nor are we modeling land use changes that might arise from changes in transit service. However, this methodology provides a much higher resolution of analysis of existing or proposed transit service and of the differential access from different communities. The results of the San Francisco Bay Area accessibility analysis indicate in general the Bay Area has relatively high levels of job accessibility by walking and transit. However, there are nuances in accessibility by annual household income and geography that indicate the current transit transportation system has room for improvement to increase the equity of transit services and access to regional job centers. Disparities in job accessibility were most pronounced between Census blocks that were in poverty or not in poverty. Current transit improvement projects in the Bay Area under construction or in the planning phase will offer improvements in job accessibility throughout the Bay Area with particular gains made in the northern Bay Area where current regional job accessibility by transit is most limited.

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