Optimizing Bikeshare Service to Connect Affordable Housing Units with Transit Service

May 2023

A Research Report from the National Center for Sustainable Transportation

Miguel Jaller, University of California, Davis

Xiaodong Qian, University of California, Davis

Raina Joby, University of California, Davis

Runhua (Ivan) Xiao, University of California, Davis

National Center for Sustainable Transportation

ITS UCDAVIS Institute of Transportation Studies

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NCST-UCD-RR-23-18	N/A	N/A

4. Title and Subtitle
Optimizing Bikeshare Service to Connect Affordable Housing Units with Transit Service

5. Report Date
May 2023

6. Performing Organization Code
N/A

7. Author(s)
Miguel Jaller, PhD, https://orcid.org/0000-0003-4053-750X
Xiaodong Qian, PhD, https://orcid.org/0000-0002-7245-3362
Raina Joby, https://orcid.org/0000-0001-5355-3854
Runhua (Ivan) Xiao, https://orcid.org/0000-0002-9676-8334

8. Performing Organization Report No.
UCD-ITS-RR-22-114

9. Performing Organization Name and Address
University of California, Davis
Institute of Transportation Studies
1605 Tilia Street, Suite 100
Davis, CA 95616

10. Work Unit No.
N/A

11. Contract or Grant No.
Caltrans 65A0686 Task Order 058
USDOT Grant 69A3551747114

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology
1200 New Jersey Avenue, SE, Washington, DC 20590

California Department of Transportation
Division of Research, Innovation and System Information, MS-83
1727 30th Street, Sacramento, CA 95816

13. Type of Report and Period Covered
Final Research Report (October 2021 - November 2022)

14. Sponsoring Agency Code
USDOT OST-R
Caltrans DRISI

15. Supplementary Notes
DOI: https://doi.org/10.7922/G2319T6M
Dataset DOI: https://doi.org/10.25338/B87P9Z

16. Abstract
This research studies the potential of bikeshare services to bridge the gap between Affordable Housing Communities (AHC) and transit services to improve transport accessibility of the residents. In doing so, the study develops an agent-based simulation optimization modeling (ABM) framework for the optimal design of the bikesharing station network considering improving accessibility as the objective. The study discusses measures of accessibility and uses travel times in a multi-modal network. Focusing on the city of Sacramento, CA, the study gathered information related to affordable housing communities, detailed transit services, demographic information, and other relevant data. This ABM framework is used to run three stages of travel demand modelling: trip generation, trip distribution and mode split to find the travel time differences under the availability of new bikesharing stations. The model is solved with a genetic algorithm approach. The results of the optimization and ABM-based simulation indicate the share of bike and bike & transit trips in the network under different scenarios. Key results indicate that about 60% of the AHCs are within 25-minute active travel time when the number of stations range from 25 to 75, and when the number of stations is increased to 100, most AHCs are within 40 mins of active mode distance and all of them are less than an hour away. In terms of accessibility, for example, having a larger network of stations (e.g., 100) increases by 70% the number of Points of Interest (for work, health, recreation, and other) within a 30-minute travel time. This report then provides some general recommendations for the planning of the bikesharing network considering information about destination choices as well as highlighting the past and current challenges in housing and transit planning.

17. Key Words
Affordable housing, bikeshare, transit, accessibility

18. Distribution Statement
No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	48	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

NCST

About the National Center for Sustainable Transportation

The National Center for Sustainable Transportation is a consortium of leading universities committed to advancing an environmentally sustainable transportation system through cutting-edge research, direct policy engagement, and education of our future leaders. Consortium members include: University of California, Davis; University of California, Riverside; University of Southern California; California State University, Long Beach; Georgia Institute of Technology; and University of Vermont. More information can be found at: ncst.ucdavis.edu.

Disclaimer

Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) and the California Department of Transportation (Caltrans) through the University Transportation Centers program. The authors would like to thank the NCST, the USDOT, and Caltrans for their support of university-based research in transportation, and especially for the funding provided in support of this project.

NCST

Optimizing Bikeshare Service to Connect Affordable Housing Units with Transit Services

A National Center for Sustainable Transportation Research Report

May 2023

Miguel Jaller, Department of Civil and Environmental Engineering, University of California, Davis

Xiaodong Qian, Institute of Transportation Studies, University of California, Davis

Runhua (Ivan) Xiao, Institute of Transportation Studies, University of California, Davis

Raina Joby, Institute of Transportation Studies, University of California, Davis

NCST

TABLE OF CONTENTS

List of Tables

List of Figures

List of Acronyms

Acronyms	Definition
HUD	Housing and Urban Development
HIP	Housing Incentive Program
TOD	Transit Oriented Development
AHC	Affordable Housing Communities/Projects
NHTF	National Housing Trust Fund
LIHTC	Low Income Housing Tax Credit
RAD	Rental Assistance Demonstration
SACOG	Sacramento Area Council of Government
SHRA	Sacramento Housing and Redevelopment Agency
POI	Point of Interest
BSS	Bike Share System
LEHD	Longitudinal Employer- Household Dynamics
GTFS	General Transit Feed Specification
ABM	Agent Based Model
GA	Genetic Algorithm
OD	Origin Destination
OTP	Open Trip Planner
FTA	Federal Transit Administration
VMT	Vehicle Miles Travelled
VKT	Vehicle Kilometers Travelled

Optimizing Bikeshare Service to Connect Affordable Housing Units with Transit Service

EXECUTIVE SUMMARY

Affordable housing developments and transit accessible developments have been two key focuses of housing and urban development agencies at national, state, and regional levels. In most cases, they are considered and planned separately. As a result, over the course of time, the spatial gap between affordable housing and transit services has been growing leading to mobility equity issues. As car ownership could be low in affordable housing communities, public transit services significantly complement the limited access to personal vehicles if the residents can access transit services within reasonable travel time and effort. Thus, a spatial joint of affordable housing communities and transit services could provide broader social benefits, including increased accessibility. However, various challenges including, but not limited to, lack of incentives for builders to construct affordable housing in transit accessible sites and high price of land near transit services make it difficult to do so.

Bikeshare, as an emerging mobility, could help address this spatial gap between affordable housing communities and transit services. Thus, we designed a bikeshare station (BSS) location optimization model that considers mitigating the impacts of this spatial gap using bikeshare services. Specifically, we propose a multi modal agent-based modeling (ABM) and simulation framework with the objective of minimizing total travel time by introducing bike share stations in the network with the goal of increasing accessibility to existing transit service. This framework estimates the travel time difference before and after introducing bike share stations in the travel network. The optimal locations of bike share stations are found using a genetic algorithm heuristic. Numerical analyses in the Sacramento city area consider scenarios including four different maximum number of bike share stations (i.e., 25, 50, 75, 100 station) to sit, estimates the saved multi-model travel time, and further improves accessibility of residents from affordable housing communities.

The optimization results lead to the following key findings. First, we conclude that using a multimodal ABM simulation framework can help measure accessibility benefits from multimodal transportation systems. Secondly, this methodology helps us to identify the minimum number of bikeshare stations needed to reach a desired coverage in the case study area. The results indicate that about 60% of the AHCs are within 25 min radius by walking when the number of stations range from 25 to 75. But when the number of stations is increased to 100 most AHCs are within 40 mins of walking distance and all of them are less than an hour away by walking. Moreover, when the number of stations is large (e.g., 100), the average count of points of interest (one type of accessibility measure) included in a 30-minute travel buffer of AHC residents increases by around 70%. Finally, there is a need to separately consider short-distance travel demand and long-distance travel demand to ensure full utilization of bikeshare services considering land use. In relatively denser parts of the city such as the downtown region, short-distance trips are more likely to directly connect originations and destinations;

while bikeshare stations are suggested to be closer to transit stations to meet long-distance trips originating in suburban parts of the city.

In sum, bikeshare stations can help residents of AHCs by increasing their accessibility to job, recreational, healthcare, and other destinations by connecting them to transit stations if effectively coupled with policies and programs that complement and encourage the use of this system. There are two main recommendations for the successful implementation of bikeshare to bridge the gap between AHCs and transit services:

- Introducing a travel survey for the residents of AHCs to study their travel behavior and understand their preferred destinations for different trip purposes. This will help to tweak the proposed multi-modal ABM to consider the actual travel and destination choices of the residents into account at the trip generation stage.
- Conducting programs to increase awareness around the usage of bike share services especially in the suburban regions and develop financial incentives to help create and maintain good bike infrastructure in these regions.

Introduction

Unaffordable housing costs are one of California's most pressing challenges. Households paying more than 30 and 50 percent of their income towards housing are considered as "cost-burdened" and "severely cost burdened" respectively. More than half of Californian residents paid over 30% of their income towards housing in 2017 and the people most affected by this are low-income households and people of color (Kimberlin 2019). Affordable Housing Communities (AHC) is the government's response to this crisis. Affordable housing is defined as housing on which the occupant is paying no more than 30 percent of their income for housing costs and utilities. Generally, a household or family with an income equivalent to or less than 65 percent of the median income of an area is eligible to apply for affordable housing in that region.

Over the past two to three decades various AHCs have been formed across the state of California. These apartments or townhomes are either in housing communities meant for low-income households alone or are in communities where not less than 20 percent of the units are occupied by very low-income families, in compliance with the National Affordable Housing Act ("National Affordable Housing Act"). Currently there are around 5800 AHCs with about half a million units across the state funded by the Low Income Housing Tax Credit (LIHTC) and many more created through other federal, state, and county wide funding sources. However, they are not nearly enough to mitigate the problem of affordable housing.

Equitable access to transit services is a critical issue, especially among low-income households and disadvantaged populations. Easy access to transit is one of the most desirable characteristics of residential areas and communities. To achieve this, planners try to create dense, walkable, mixed-use developments at a walkable distance from transit. Developments that are designed to be accessible by public transit and include a mix of residential, commercial, and recreational spaces are sometimes referred to as Transit Oriented Developments (TOD). They help to encourage people to use public transit and other sustainable modes to access jobs, healthcare, recreational facilities, and other destinations thereby creating sustainable communities. The downside is that the demand for housing in such areas is high and this naturally causes the rent and housing prices to spike, making them unaffordable for low-income families.

Federal and local housing and urban development agencies have been actively trying to address the issue of lack of affordable housing through multiple programs and policies. These programs generally tend to follow three basic approaches that include rental assistance, homeownership assistance, and land use and regulatory incentives ("Affordable Housing Policies: An Overview" 2016). LIHTC was created in 1986, HOPE IV and Choice Neighborhoods Program initiated in 1990s, and New Market Tax Credit created in 2000 are some examples for such programs. The Federal Transit Administration's (FTA) New Starts and Small Starts programs provide funds for construction of new fixed guideway systems or extension of existing systems by considering transit supportive land use and economic development effects, thus enabling creation of more TODs. Most of these programs in the past focused on only either one of these issues and did not consider navigating the affordable housing crisis and need for TODs simultaneously. This glitch in the planning process led to a spatial gap between AHCs and transit services. As reported by Boarnet (Boarnet et al. 2017), combining transit-oriented development (TOD) and building affordable housing can yield greater benefits in terms of both reduced driving and more affordable housing.

Realizing the need for AHCs in transit accessible sites, different initiatives to accomplish the same have been recently introduced. For example, the Federal Department of Housing and Urban Development (HUD) is pursuing housing programs to be better connected with transit services. Amongst the local governments, the Bay Area Metropolitan Transportation Commission's Housing Incentive Program (HIP), for instance, offers financial awards in the form of transportation funding to local jurisdictions that locate compact housing within one-third of a mile of transit. Even though transit agencies in several cities have exchanged discounts on land costs for commitments to affordable housing based on anticipated higher transit ridership, there still exists the problem of incorporating TOD and affordable housing conceptually and practically in the planning process. These include but are not limited to high prices of transit accessible sites and lack of incentives for contractors and developers to bring cheap and affordable housing at transit accessible locations. Various studies and analyses performed over the past decade highlight similar challenges to mitigate the barriers between affordable housing and transit services.

Currently, bikeshare has shown great potential to improve accessibility, particularly for disadvantaged populations (Qian and Niemeier 2019). Recent research conducted by the team has evidenced the close relationship between housing and accessibility to jobs and other desirable destinations to promote the use of bikeshare among disadvantaged populations (Qian and Jaller 2021; 2020). Moreover, there is additional evidence that micromobility could also help bridge the transit access gap. For example, in San Francisco, a significant share of bikeshare trips start or end near transit stations. Recently, the research team analyzed the role bike share (and other micro-mobility services) played to supplement reduced transit amid the COVID-19 pandemic (Qian, Jaller, and Circella 2022). Therefore, this project takes on the question of whether emerging micromobility (i.e., bike share) can help reduce the gap and connect those two important components in urban planning. It is important to acknowledge that providing access to bikeshare is a necessary condition for its use but is not a sufficient condition. Thus, addressing the deficit between desirable destinations (e.g., jobs) and origins (affordable housing), will help support the use of bikeshare, and show its potential to mitigate the housing and TOD identified problems.

To evaluate the hypothesis, this project conducts mathematical modeling and develops an optimization framework to optimize the location of bikeshare stations to mitigate the barriers between affordable housing and transit services. This optimization process considers both bikeshare trip demand, transit service schedule, available affordable housing units, and other geographic information. The optimization results provide bikeshare planning suggestions to connect affordable housing units and transit services. The research uses Sacrament as a case study to implement the framework.

The subsequent sections of the report are structured as follows. The next section discusses a detailed literature review followed by the description of the case study area and the data used for the analyses. This is succeeded by a section that provides the details of the optimization methodology. Next, the report summarizes the numerical results and concludes with a few planning recommendations and recommendations for future research.

Literature Review

This section discusses relevant literature in two parts. The first summarizes the literature surrounding affordable housing, and the concept and relevant practices of Transit Oriented Development. The second part concentrates on literature related to metrics and models used to quantitatively measure accessibility.

Affordable Housing and Transit Oriented Development

According to the National Affordable Housing Act, HUD designates housing as affordable if the gross costs to live in that housing unit, including utilities, do not exceed 30 percent of the adjusted income of a family whose income is equal to 65 percent of area's median income. This threshold of 65 percent may vary for different regions if deemed necessary by the Secretary because of existing construction costs, fair market rents, and other economic factors. In Sacramento County, households whose earnings do not exceed 60 percent of the area's median income are eligible for affordable housing.

TOD is defined as a type of urban development designed to have all important destinations within walking distance of public transit services. Such developments are considered critical for the development of sustainable communities and to increase transit ridership. Some research on TOD has been directed towards analyzing the effects of TOD on travel behavior (Ibraeva et al. 2020). An analysis of TOD in metropolitan areas reveals that people living in TODs tend to reduce car usage, thereby reducing their VMT by 38% and 21% in Washington, D.C. and Baltimore respectively (Nasri and Zhang 2014). A similar study investigated effects of residential self- selection and effect of built environment on the travel behavior of the residents of TOD and Non-TOD areas in Shanghai city. Results of in person interviews showed that almost 70% of commuting trips were made by transit in TODs, almost double of what was observed in non-TOD areas. On the other hand, people residing in Non-TOD areas were twice as likely to commute by car (Chen et al. 2017).

However, the proximity to TOD areas increases property prices in adjacent areas leading to densification and/or gentrification over time. To construct affordable housing, most development projects tend to locate away from transit accessible sites, and most residences in TODs tend to be expensive, both owing to high real estate prices of transit accessible sites as mentioned before. This means that low-income groups residing in AHCs tend to have relatively less access to transit services when compared to the economically well-off groups. The irony here is, according to research, very low-income households (less than or equal to 30% the area median income) have a greater need for public transportation services to connect them with job opportunities due to less or no access to private vehicles and other more expensive modes of travel (Haughey and Sherriff 2011).

The spatial gap between AHCs and transit services can be eliminated by creating AHCs in transit accessible sites. But this seamless integration of AHCs and TODs is met by several challenges. Two major current challenges are: the expiring of current affordable housing programs and the lack of enough incentives to attract housing developers to provide cheap housing near transit stations and job centers (Haughey and Sherriff 2011). Nedwick & Burnett interviewed housing agencies and transit policy experts to uncover more challenges: the conflicting priority between locating LIHTC housing and transit access, and the high cost of developing transit-accessible sites (Nedwick and Burnett 2015). It is essential to understand that transportation and housing planners must work together to find development locations with high transit connectivity and not simply a short distance to the nearest transit stop (Welch 2013). Recent research suggests that affordability restrictions targeted at new housing constructed in TOD are effective tools for promoting housing affordability and improving low-income households' access to transit (Dawkins and Moeckel 2016).

Accessibility

While on one hand, the reason for the spatial gap between AHPs and transit services and viable solutions to the same are being studied, on the other hand several efforts have been made to measure or quantify accessibility to understand the quality of a transportation system. This section summarizes these methodologies.

Accessibility is defined as a convenience measurement of an individual to travel to a desired destination or point of interest. It is often used as a metric to determine the quality of a transportation system or network. Over the years, different models have been developed to determine accessibility. Generally, these models can be classified into three categories: Cumulative Models, Gravity Models and Utility based Models. Cumulative models also known as Count or Isochronic models evaluate an individual's accessibility as the cumulative number of opportunities within a specific radius of time or distance from his/ her point of origin. In this case, a higher number of opportunities indicates higher accessibility. The simplicity of this model makes it desirable. However, this model functions under the assumption that each opportunity accessible to an individual is equally attractive, which is not the case. Gravity models consider the accessibility of an individual from a specific zone of residence to the destination zone. Here, accessibility is a function of the distance between the zones or time taken to travel from one zone to the other and the attractiveness of each destination zone. The attractiveness of an opportunity is quantified using parameters like number of employees or square footage of the facility, among others. Finally, utility-based models incorporate individuals' behavior and decision-making preferences into consideration to calculate accessibility. These models can provide a picture of true accessibility levels for different individuals by going a step ahead of gravity models and weighing each opportunity based on user preference. Such models require a large amount of data including travel behavior surveys. Table 1 shows the equations describing each model.

Table 1. Accessibility Models and their Equations 1, 2 and 3

S. No.	Accessibility Models	Equations	Description
1.	Cumulative Model	$A_{CM,i} = \min_{\forall k} d_{ik}$	i=zone index; k=opportunity index; d=distance to opportunity
2.	Gravity Model	$A_{GM,i} = \sum_{k=1}^{N} \left(\frac{S_k}{d_{ik}^{\delta}} \right)$	i, d, k=same as above; S=attractiveness of opportunity (e.g., square footage of facility)
3.	Utility Based Model	$A_{UBM,i} = \sum_{j=1}^{M} \sum_{k=1}^{N} f_{kji} \cdot w_{kji}$	i=zone index; j=individual index; k=index of characteristic; M=population of zone; N=number of characteristics; f=relevant characteristic (delay); w= weight assigned to f

Different researchers have attempted to formulate such models for different modes or trip purposes. Gravity models are relatively more popular and have been used by researchers in different contexts to evaluate accessibility. LaMondia et al. developed a two-step cluster gravity model to measure patrons' accessibility to healthcare facilities using paratransit services by considering a parameter that describes each facility's availability relative to the region's population in addition to the facility's square footage as a measure of its attractiveness (LaMondia, Blackmar, and Bhat 2011). Chandra et al. developed a gravity model to determine optimal number of transit stops for fixed route and demand route transit services by maximizing accessibility or in other words minimize time impedance between origin and destination (Chandra et al. 2013). Comparing the accessibility results obtained from different models showed that all the three models give dramatically different results and cannot be duplicated. Also, as we progress from cumulative models to utility-based models, the data intensiveness increases but the results are more accurate. Additionally, authors pointed out that it is always best to determine accessibility for one mode and purpose combination for accurate results (LaMondia, Blackmar, and Bhat 2011).

Apart from accessibility models, different researchers have worked on defining the parameters within these models to improve their accuracy. These parameters are called impedances. Distance to the nearest transit stop or station, travel time, and costs are some examples of impedances. The longer the distance and the travel time, the lower the accessibility. M. Iacono et al. estimate distance-decay functions to determine the impedance of travel distance or time across different modes and trip purposes (Iacono, Krizek, and El-Geneidy 2008). Their findings suggest that travel distance, especially for walking, exceeded the assumed threshold of a quarter mile. Similarly, impedance of travel distance for biking and public transit modes for different trip purposes have also been investigated in the paper. Polzin, Pendyala and Navari emphasized that it is important to consider both spatial and temporal dimensions of demand and supply to determine accessibility. They considered the time-of-day distribution of travel demand and transit supply and schedule during different time periods to incorporate the temporal aspect of accessibility (Polzin, Pendyala, and Navari 2002). Cheng et al. further integrated transit time table and passenger departure time in a full network time prism to determine dynamic individual spatial-temporal accessibility by public transit for any given passenger departure times (Cheng et al. 2018). To measure accessibility as a dynamic index by considering overcrowded conditions in metros, a gravity model that considered the capacity of a metro line, the number of passengers on a metro line real-time (using swipe in and swipe out counts of passengers at every stop) in addition to other factors like waiting time, the attractiveness of the destination was also used. This methodology helped them to estimate the real-time accessibility of an individual to a destination by metro at different times of the day (Li et al. 2020). Bills and Carrel noted that most methodologies that calculated accessibility did not consider travel time unreliability which risks mischaracterization of the accessibility experienced by users. To tackle this problem, they proposed using the total travel time budget in place of total travel time. This travel time budget is estimated using a high percentile of travel time distribution. Additionally, it was concluded that for different groups of people, different percentile values must be considered based on their working schedule flexibilities and this in turn may create different levels of accessibility for different groups of people (Bills and Carrel 2021).

Recent research shows that bikeshare can help improve accessibility to various destinations especially amongst disadvantaged communities (Qian and Niemeier 2019). However, the possibility of using bikeshare to bridge the spatial gap between AHCs and transit services and thereby improve overall accessibility of the residents of AHCs has not been explored yet. This research project aims to fill that gap utilizing an optimization framework with an objective function aiming to minimize total travel time by introducing bikeshare service stations. Unlike previous studies, here we use a multi-modal agent-based model to find optimal locations for stations and thereby reduce total travel time and improve accessibility.

Bikeshare Location Optimization

Geographic Information System (GIS) based optimization tools have been used in most of the current studies on bikeshare location decision (Wuerzer, Mason, and Youngerman 2012; Croci and Rossi 2014; García-Palomares, Gutiérrez, and Latorre 2012; Rybarczyk and Wu 2010; Bryant Jr 2013). Some of these studies focus on the planning and implementation of new systems while others focus on analyzing existing bikeshare systems. An example for the former would be GIS-based location optimization model for bikeshare stations in Boise, Idaho (Wuerzer, Mason, and Youngerman 2012). In their model, Wuerzer, Mason and Youngerman factors including population density, higher education, employment density, transit, bike path infrastructure, and other recreation locations to study their effect on bikeshare demand generation. Their model considered multiple scenarios of bike usage to finally recommend the number and location of bikeshare stations. Their model included a budget constraint which helped consider capital expenditure when determining the final set of recommendations. Some studies that focused on the latter include the analysis of public bike rental services in Taiwan (Wang, Tsai, and Lin 2016). Hot spots of bikes and/or bike racks (stations) deficit were identified through a spatial-temporal analysis of historical bikeshare activities followed by a trail location theory to suggest ideal rental station locations in Taipei. This study proved how useful GIS and spatial-temporal analyses can be to plan and design bikeshare systems. A similar study by Croci and Rossi looked into the “BikeMi” system in Milan to evaluate the system analyze bikeshare location problems (Croci and Rossi 2014). Their analysis revealed the fact that locating bikeshare stations near metro and train stations, universities, museums, cinemas, and restricted traffic areas significantly increase their use. They concluded that careful consideration of the surrounding environment is important for the optimal siting of bikeshare stations. García-Palomares, Gutiérrez, and Latorre formulated a GIS-based tool to optimize bikeshare station locations with the objective of minimizing impedance and maximizing coverage (García-Palomares, Gutiérrez, and Latorre 2012). They recommended the latter, which is more suitable in terms of efficiently covering potential demand. Further, they evaluated the optimal locations in terms of their accessibility to different travel activities to come up with the final number and locations for bikeshare stations.

Multiple-objective analyses is another methodology opted by researchers to evaluate current bikeshare station locations. Jahanshahi et al. applied multiple-criteria decision making (MCDM) and Jenks natural breaks classification method (JENKS) to rank and classify all available stations and stations planned for future respectively (Jahanshahi et al. 2019). Their results indicated that 51 of the 128 stations in Meshad, Iran were unsatisfactory. Additionally, examine 22 planned bikeshare stations using the same methodology and recommend potential locations for these stations. Similarly models were utilized by Bryant Jr in his study where he provided suggestions based on the multi-objective optimization results (Bryant Jr 2013).

Griffin and Jiao used public participation GIS (PPGIS) to study the influence of public participation on bikeshare planning (Griffin and Jiao 2018). PPGIS is a tool which allows the public to suggest the placement of new bikeshare stations. In their study, they used two methodologies: geographic proximity analysis and local Moran’s I (spatial correlation). The geographic proximity analysis revealed that only a small portion of current bikeshare stations were within 30 meters of stations suggested by the PPGIS. However, the Moran’s I statistic proved that the current station locations and suggested ones showed considerable clustering. They finally concluded that public input can and does affect the decisions made by planners. They suggest that the PPGIS platforms show great promise for ensuring that the planners are made aware of the public’s needs which will help curate a bikeshare plan that incorporates these suggestions.

The main feature of GIS-based analyses is it helps predict potential bicycle users or bikeshare demand which is further used to suggest optimal bikeshare locations. However, there is a lack of research incorporating real-time transit information into the optimization model which limits the ability of the model to fully assess the impact of connecting bikeshare with transit. This research will develop an optimization algorithm to decide bikeshare station locations by considering transit service at the same time, especially for residents in AHCs.

Case Study Area and Data

Case Study Area

For this project, we have considered the City of Sacramento as our case study area. Active transportation has been one of the strategic focuses of the California Department of Transportation (Caltrans) and the Sacramento Area Council of Government (SACOG) for almost a decade now. Various efforts to promote active transportation include but are not limited to, developing better biking infrastructure, and introducing bikeshare programs. Currently Lime, Bird and Razor have their bikes and e-scooters operating in the city. Additionally, both docked, and dockless (or free-floating) bikeshare systems operate in the city giving users more flexibility. As of 2020, the city of Sacramento led the nation for JUMP Bike and e-scooter use. While it hasn't been the same post COVID, we know that the city has a great potential to showcase growth in bikeshare ridership. Additionally, multiple AHPs and TODs have been funded and established by the Sacramento Housing and Redevelopment Agency (SHRA) and California Department of Housings and Community Development through a combination of multiple initiatives. This makes the city of Sacramento an appropriate choice for the case study.

The city, Sacramento, shown below in Figure 1 is expected to grow manifold with increasing job opportunities which will further worsen the affordable housing crisis. This calls for more well-connected AHC in the city.

Study Data

This study uses data from different sources. They include Affordable Housing Communities Data, demographic information from the American Community Survey, OpenStreetMap road network (drive, bike and walk network), Points of Interest (POIs) data, General Transit Feed Specification (GTFS) data, and Longitudinal Employer-Household Dynamics (LEHD) data, each of which will be described in brief in the following subsections.

Affordable Housing Projects Data

The Sacramento Housing and Redevelopment Agency maintains an inventory of Affordable Housing Projects funded by them (CTCAC 2021). Similarly, the office of the State Treasurer also maintains a list of Multifamily Housing Projects developed using the LIHTC program in California. The data from these two sources was used to create a combined list of the affordable housing projects (AHPs) in the city limits including information such as the name of the project, address, and number of affordable housing units, among others.

The data was inspected in detail to identify and eliminate duplicates in the combined list and other old projects that were eventually scrapped. The final list consisted of 149 AHPs spread across the city. Figure 2 shows the spatial distribution of these AHPs and the histogram in Figure 3 shows the count distribution of Affordable housing projects. On average, each AHP consists of around 113 units.

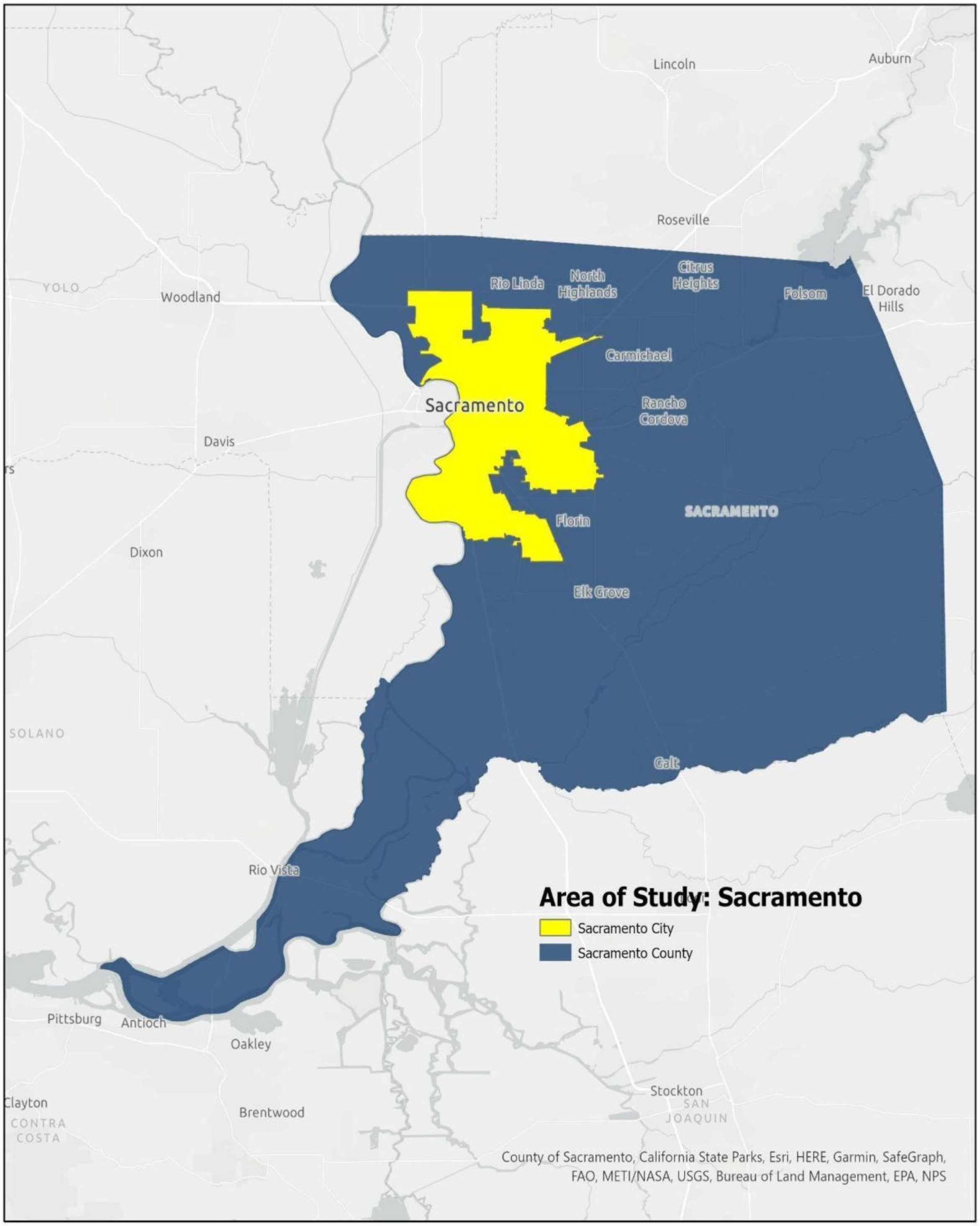


Figure 1. Area of Study - City of Sacramento

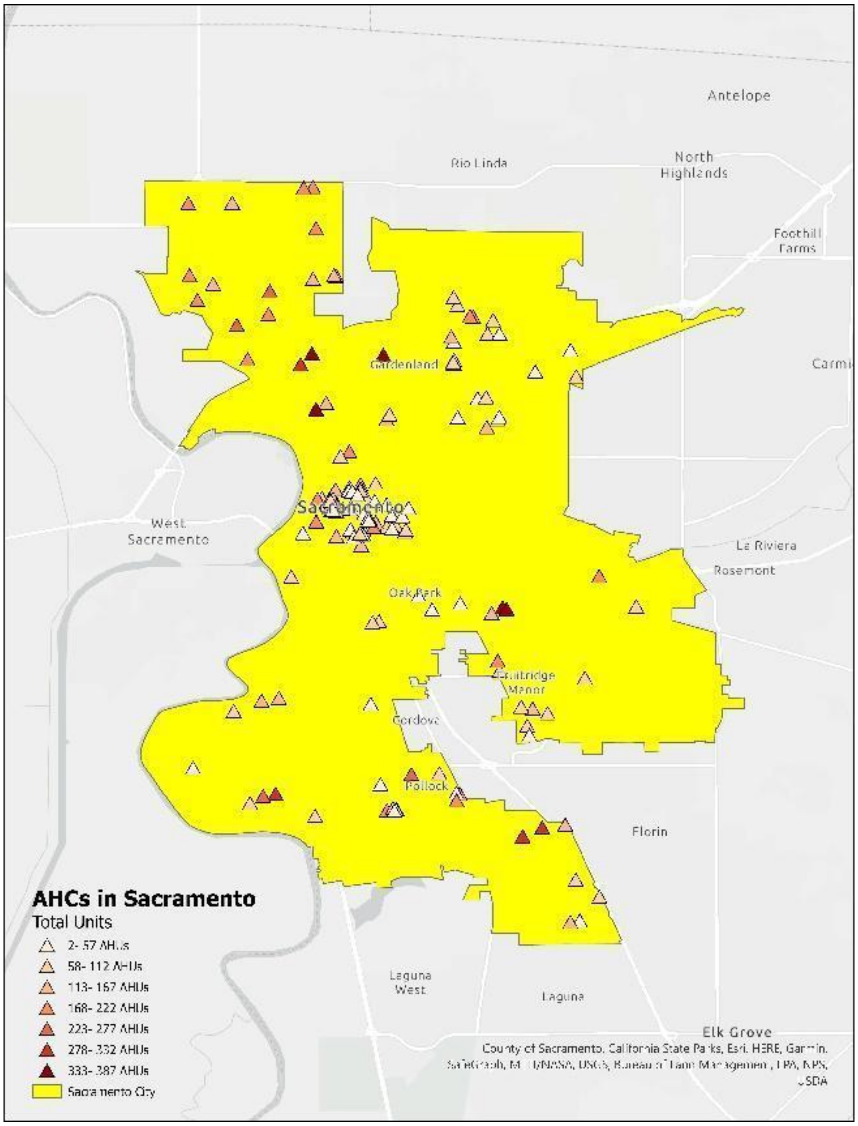


Figure 2. Spatial distribution of AHCs by total units

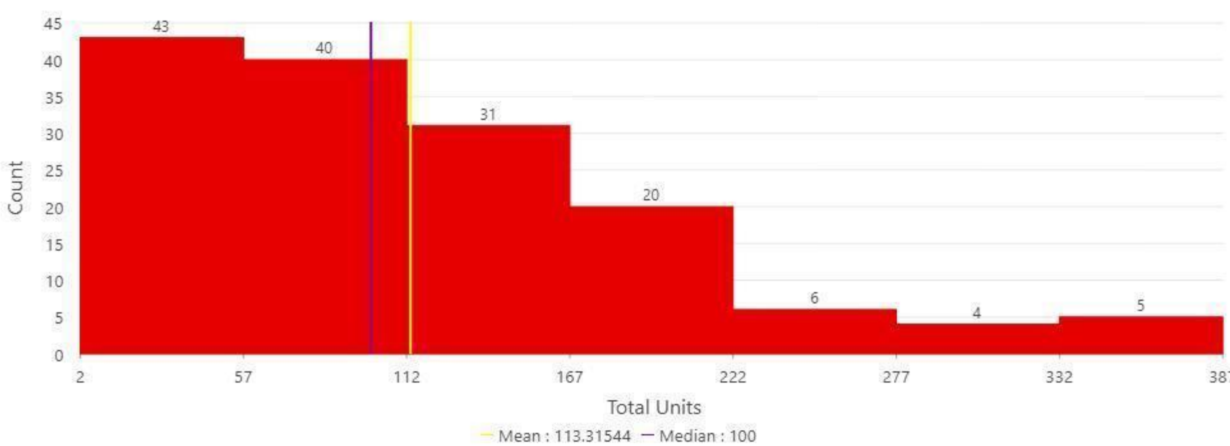


Figure 3. Histogram of Units in AHCs

Demographic Information

Population demographics like household income, number of family and non-family households, number of occupied and vacant housing units were sourced from the 5-year estimates of 2020 American Community Survey data (US Census Bureau n.d.). All variables considered for the study have been gathered at census block group granularity.

The survey data has been used here to estimate the population of AHCs used in the optimization problem to estimate trips generated. For this, the low-income households (less than or equal to 60 % of area median income as defined by SHRA) in each census block group are filtered. The proportion of these households with respect to the total number of households are calculated. An average occupancy value per household is then calculated by using the number of family and non-family households from ACS data. This occupancy value is then used to estimate the population in AHCs assuming that the household and income characteristics of census block groups where 75% or more of its households are low income resembles the characteristics of the households in AHCs.

However, due to the data restriction, we cannot get access to the demographic information of each individual household in AHCs. Thus, there is no information for whether a household has children and how old children are. This data limitation will restrict the following individual trip generation and this study adds specific assumptions to address this limitation. Please refer to the following methodology section for more details.

Longitudinal Employer-Household Dynamics (LEHD) Data

The LEHD Origin-Destination Employment Statistics or LODES data made available by the US Census Bureau was used to identify OD matrix with census blocks with residences/homes as origin and the census blocks with workplaces/ offices as destination (US Census Bureau for Economic Studies n.d.).

Bike and Walk Network Data from OpenStreetMap

Biking and Walking network data were sourced from OpenStreetMap API for the city of Sacramento (OpenStreetMap n.d.). The network attributes include name of the road, length of segments, class of the roadway segment (residential, primary, secondary). We assume the speeds of biking and walking are 4.2 m/s and 1.2 m/s, respectively, in the ABM simulation.

Points-of-Interest (POIs) Data

Points of Interest data from OpenStreetMap were obtained for Northern California from which the points of interest in the city of Sacramento were filtered. There were around 93 classes of POIs in this dataset, which was regrouped into 5 categories, decided based on transit trip purpose survey (Trip purposes in U.S. public transit). The five categories, except work, considered for the study are medical, shopping / eating out, school, recreation and other (see Figure 4). From Figure 5, these POI were considered as some of the destinations for the affordable household residents in the city. Based on the data most POIs came under the category of shopping/eating out.

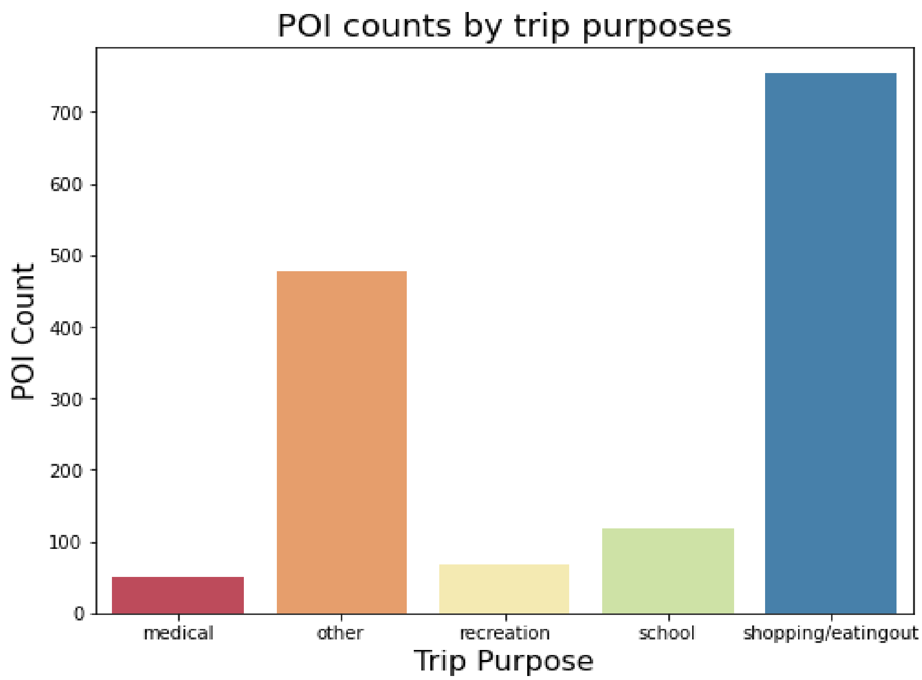


Figure 4. Count distribution of POIs

General Transit Feed Specification (GTFS) Data

The General Transit Feed Specification or GTFS is another critical dataset required to measure accessibility of residents of the identified AHPs to various points of interest. GTFS data for the study were sourced from the Open Mobility data website which included routes, stops, stop times and sequences (SACRT GTFS).

The Sacramento GTFS transit line data are shown in Figure 6. The case study area, Sacramento, is linked by 70 routes and more than 2500 stops through Sacramento regional Transit (SacRT) and South County Transit Link services. SacRT consists of 64 bus routes and three light rail lines (blue, green, and gold). Finally, the South County Transit link has three bus routes connecting different parts of the city.

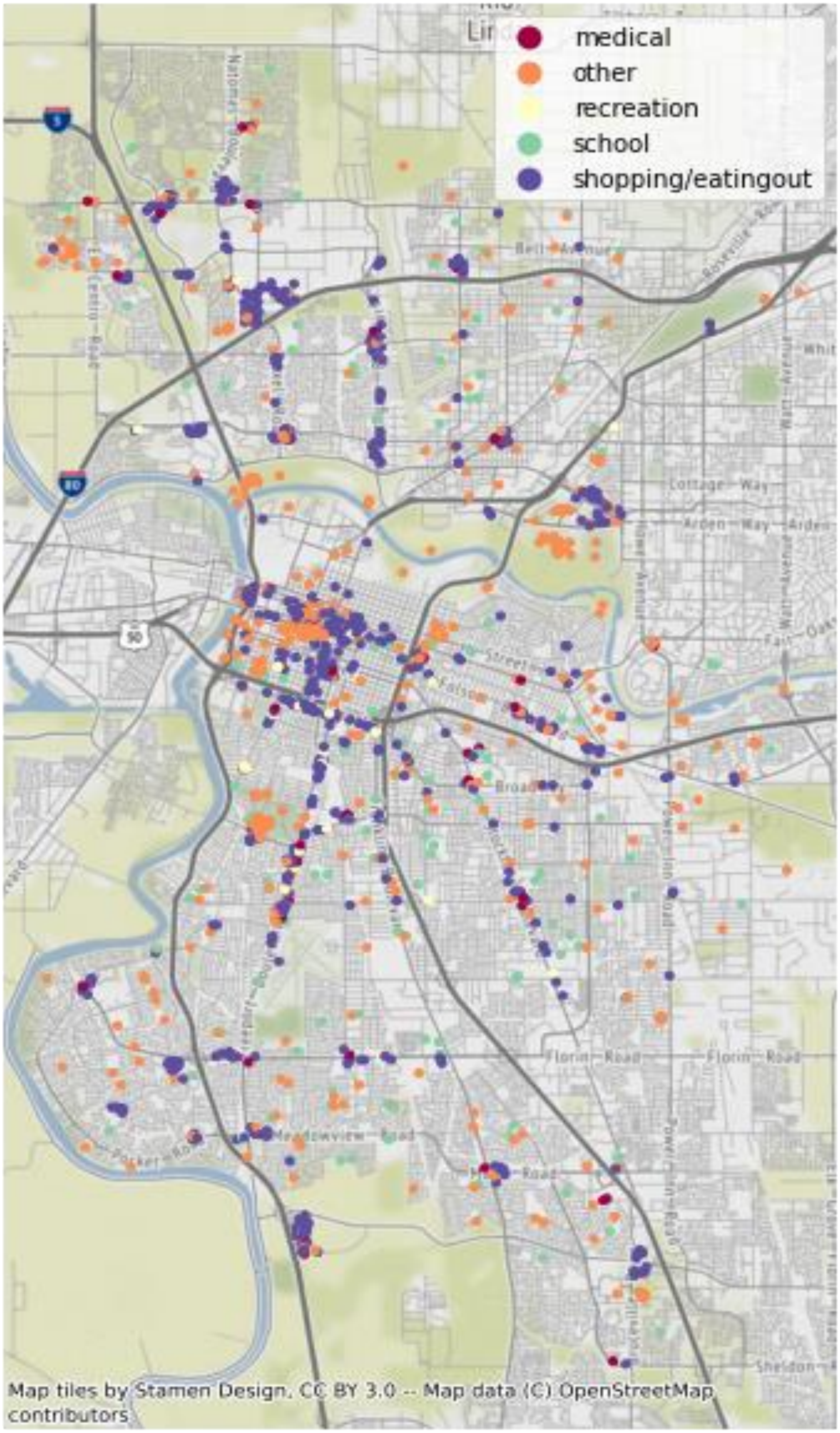


Figure 5. Points of Interest identified in and around Sacramento

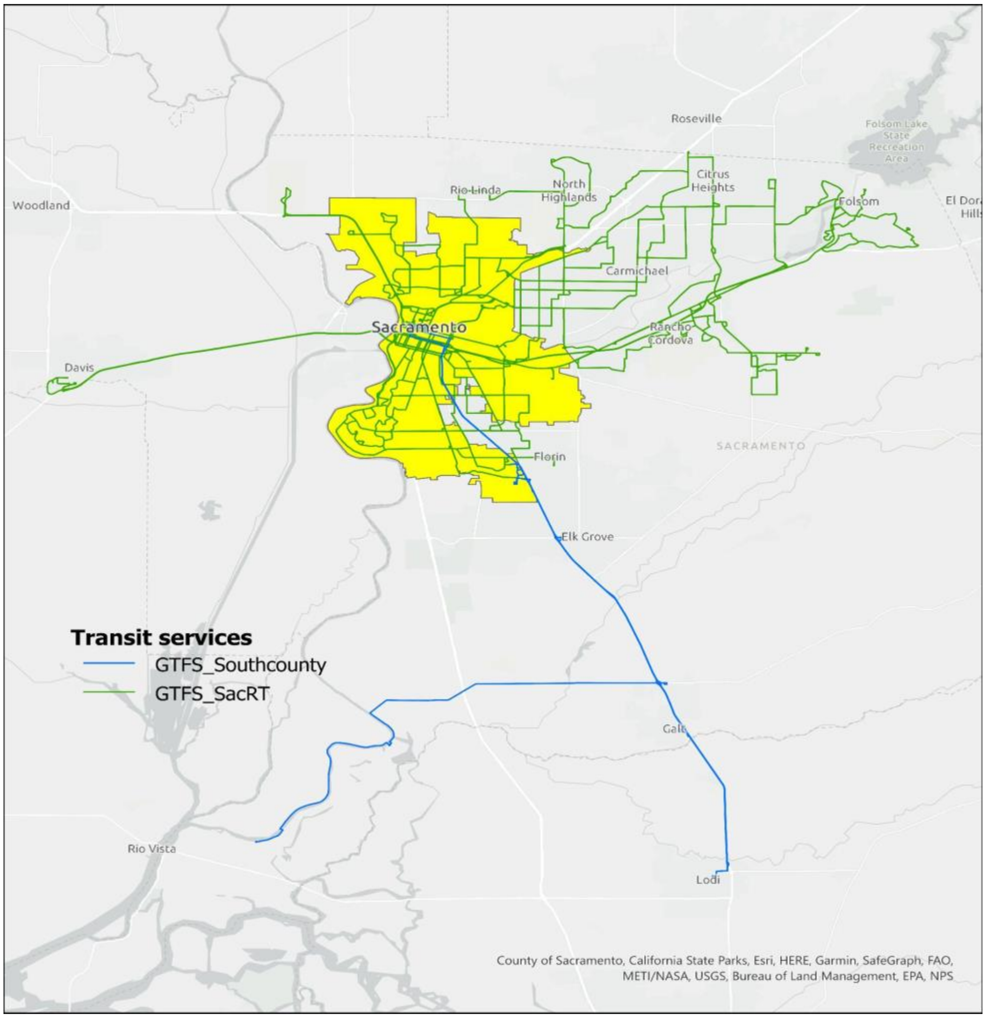


Figure 6. Transit services in Sacramento

Methodology

This project studies an optimization problem for the locations of bikeshare stations (BSS) to mitigate the barriers between affordable housing communities (AHC) and transit services. To solve this optimization problem, we propose a multi-modal agent-based model to find the optimal location of BSS by combining the use of mathematical programming, agent-based model (ABM), individual multi-modal route planning, and heuristic algorithms. These four components are nested into a genetic algorithm (GA)-based framework, see Figure 7. First, we define the objective function for the optimization of the GA. Then we import spatial data such as AHC, POI and LEHD, as well as GTFS transit data, and OSM street data. Given a selection of k BSS from all candidate locations, the random solutions (with the length of the population size set up) is initialized. Then a single ABM simulation is performed and if the maximum number of iterations is not reached, the solution set is updated. The GA will eventually output the solution that makes the objective function optimal. Also, ABM can output other disaggregate indicators for more analysis.

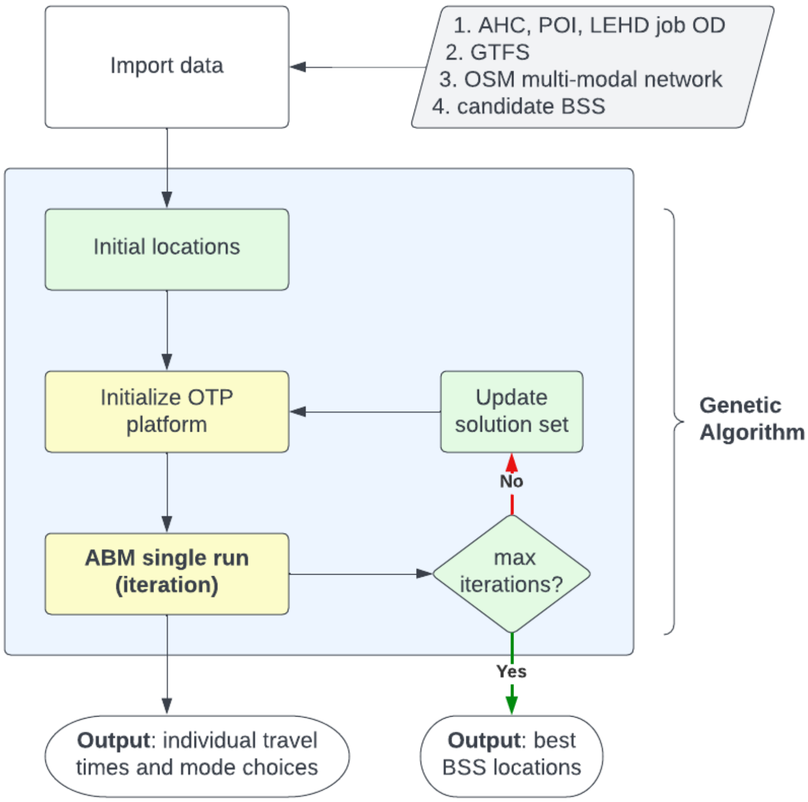


Figure 7. Technical Scheme

ABM Simulation Framework

The basic analysis unit of the ABM model used in this project is the residents of AHCs, and we use a travel-based simulation approach. Without considering traffic assignment (i.e., street traffic flow, congestion, among others), we simulate the residents' travel process in three stages: 1) trip generation; 2) trip distribution; and 3) mode choice. Although the three stages are derived from the traditional four step model using aggregate analysis methods, they can be manifested and decomposed into different decision stages for every single individual in disaggregate analyses using ABM. All three stages are completed, and the related attributes are simulated in a single run of ABM, for all residents simulated. Since this project only considers multi-modal travel accessibility for AHC residents, focusing on comparing the accessibility differences before and after the introduction of bikeshare, we do not consider traffic assignment. Also, we assume that the capacity of each BSS is large enough, i.e., no capacity constraint is considered. We describe the specific processes and assumptions for these three stages as follows.

Individual Trip Generation

The trip generation stage works as a setup process for every resident simulated, where the origin of resident is initiated, and trip purpose is assigned via weighted probabilities. We assume that all trips are home-based trips, which means that origin points are AHCs. Regarding the trip purpose weights, we adopt the 2015-2018 U.S. transit trip purpose survey results (Trip purposes in U.S. public transit - poll 2015). We use the average household size for the city of Sacramento for 2016-2020, at 2.63, to estimate the population of all affordable housing units, sourced from the U.S. Census Bureau (U.S. Census Bureau QuickFacts). This allows the ABM simulation to be performed based on a real population of affordable housing units to reflect the real travel demand from affordable housing projects. Meanwhile, this study only considers trip purposes including work commuting, grocery shopping, and recreation.

Destination Allocation

After initializing the origin and travel destination, ABM assigns destinations to the resident depending on the destination. The process of assigning destinations is shown in Figure 8. For the travel purpose of work, the model finds the workflow corresponding to the census block to which the AHC belongs according to the LEHD data, then finds the individual census blocks of the work destination, and finally generates random points as the destination. For the trip purposes of different POI other than work, we assign the nearest POI to residents as their destinations based on the proximity principle.

Individual Mode Choice

In the first two phases, the model assigns origin and destination (OD pairs) to each resident, and when making mode selection, the model inputs the OD pairs to the open trip planner (OTP) platform for route planning. For each alternative travel mode, the best path (i.e., least travel time) is selected. In this case, we set a walking distance threshold of 0.5 mi for transit and bikeshare in the route search via OTP (see a route inquiry interface of OTP in Figure 9). We assume that residents choose their travel mode based on the principle of maximizing time utility, so the travel mode with the shortest travel time will be selected by the model.

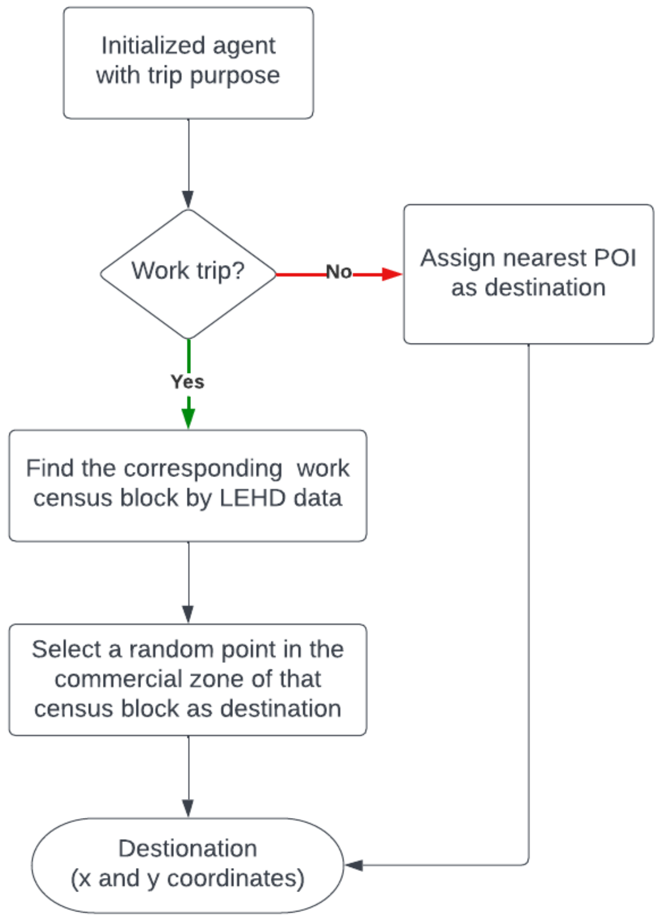


Figure 8. Destination assignment logic

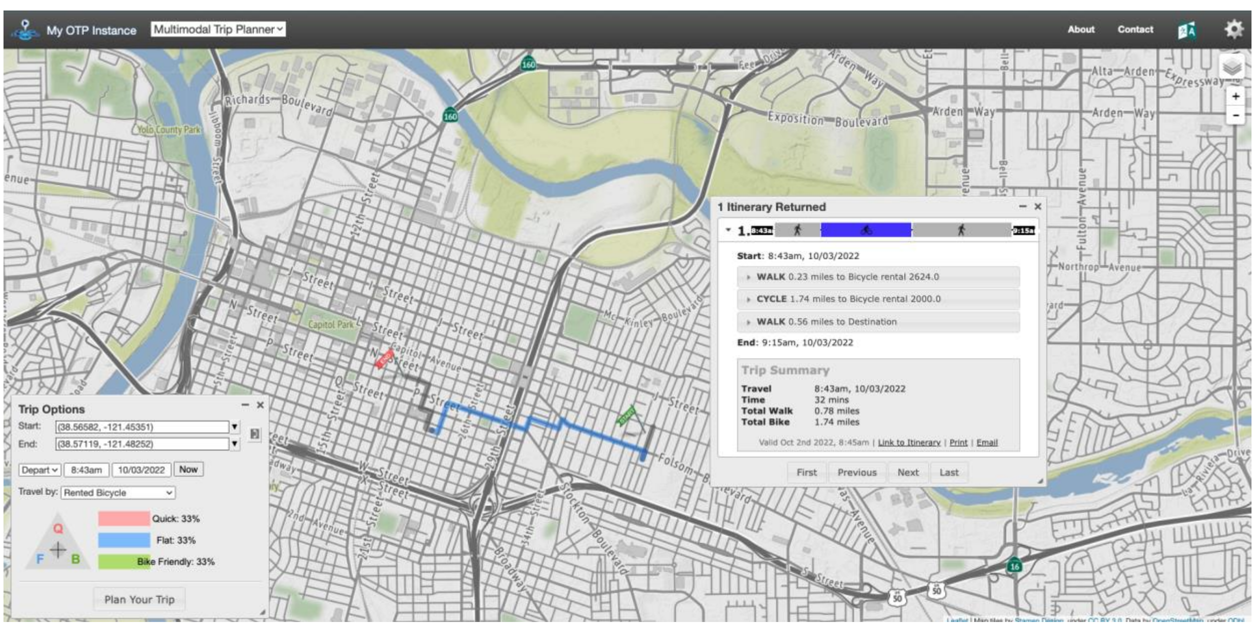


Figure 9. OTP route inquiry interface

Estimation of the objective function value (single run of ABM simulation)

The ABM simulation idea is implemented to serve as an estimate of the objective function value when solving the location optimization problem in this heuristic algorithm. Every iteration in the algorithm returns the objective function value for optimization, which is provided by a single ABM run. Due to the feature that trips simulated in ABM are not parametric and linear, the ABM single run is not in the form of a linear function that can be decomposed parametrically and cannot be solved using a gradient descent method. The input for a single ABM run is the index of BSS stations selected from the candidates, and the output is total travel time saved by BSS, serving as the objective function value that will be discussed in the next paragraph. The steps of a single ABM run are described below.

- ***Environment setup***
  ABM sets up all inputs and required road network data, including: the BSS location choice set (from candidate station locations), multi-modal network (walk, bike, and transit), point locations (AHC, POI and LEHD job data, selected BSS, transit stops), and time window (on-peak/off-peak, weekdays/weekends).
- ***Initialize agents***
  All agents in the simulation are initialized with their corresponding trip purposes, demographics, origins (residences from AHCs).
- ***Destination allocation based on trip purpose***
  For each agent's different travel purposes, we assign destination points to them based on LEHD data if it is a work trip, and we assign the nearest POI points to them if it is other travel purposes.
- ***Individual mode choice***
  We use OTP to simulate all individual routes over all modes for the agent to select the optimal travel mode based on maximum time utility criteria.
- ***Aggregate accessibility measurements***
  The single ABM run provides aggregate indicators for estimating the objective function value (see the next sub-section discussing location optimization problem).

BSS location optimization problem

The location optimization problem for BSS can be reduced to an optimal point selection problem based on the complete graph. We reduce the multi-modal traffic network to a basic graph containing a set of n vertices V, and $(n/2)$ weighted edges with weights d_{ij} which are multimodal travel times of network road segments. In the classical k-median problem, where it finds k optimal points to minimize total impedance, the aim is to find a subset (facilities) such that the total weights on edges from each vertex of G (demand points) to the nearest vertex of S is minimized.

We create the 500 candidate BSS locations using K-means clustering method geographically on the demand points (AHC) and the POI. Figure 10 shows the candidate BSS for the optimization, with a total number of 500 locations and delivers the corresponding Voronoi diagram using

Manhattan distance criteria. Those colored regions are formed by dividing the space around each point into a series of lines or curves called Voronoi edges, which are perpendicular to the lines connecting the point to its nearest neighbors. The resulting Voronoi diagram would show the regions of the plane that are closest to each BSS, and the size of each region would indicate the coverage provided by that BSS.

By comparing different facility locations and the resulting Voronoi diagrams, you can see which locations provide the best balance between coverage and the number of facilities needed. This can help you make informed decisions about where to locate the facilities to maximize their effectiveness.

In the k-median problem, there are two types of vertices: demand points and facilities. The problem aims to minimize the total impedance from all demand points to all facilities in the network. Typically, scholars define the impedance using travel time and/or distance from demand points to facilities. The problem with the traditional k-median is that it only calculates the distances from demand points (AHC) to facilities (BSS), without considering the role played by the BSS as an intermediary point in different trips, and it does not calculate the multimodal accessibility. To this end, we propose an ABM-based algorithm for the location optimization problem.

The definition of the BSS location optimization problem is as follows.

$$\min_{\boldsymbol{S \subseteq V, |S| = k, k \leq n}} \sum\nolimits_{\boldsymbol{i \in O, j \in D}} \min_{\boldsymbol{a \in A, b \in B}} (\boldsymbol{t_{ij,b} - t_{ij,a}}) \qquad \textbf{Equation 4}$$

where S is the subset of location choices (k stations) of all candidate locations V (n locations), O and D are the sets of all demand points (AHC) and all destinations for different trip purposes, $t_{ij,\alpha}$ is the pairwise network impedance (multi-modal transit travel time) of a specific mode in all travel alternatives without BSS, $\alpha \in A$ and $b \in B$. Set A includes transit travel modes without bikeshare and set B includes bikeshare.

When calculating t_{ij}, we use ABM to simulate the travel times from AHC to BSS in the network. Since the starting end point of t_{ij}, each individual is not constant when using ABM for individual analysis, we calculate the total travel time saved by bikeshare of all individuals in the network as the objective function. This can be changed and minimized with the optimal selection of k BSS in the network, which also enables the feasibility of using heuristic algorithms to obtain an approximate optimal solution more efficiently.

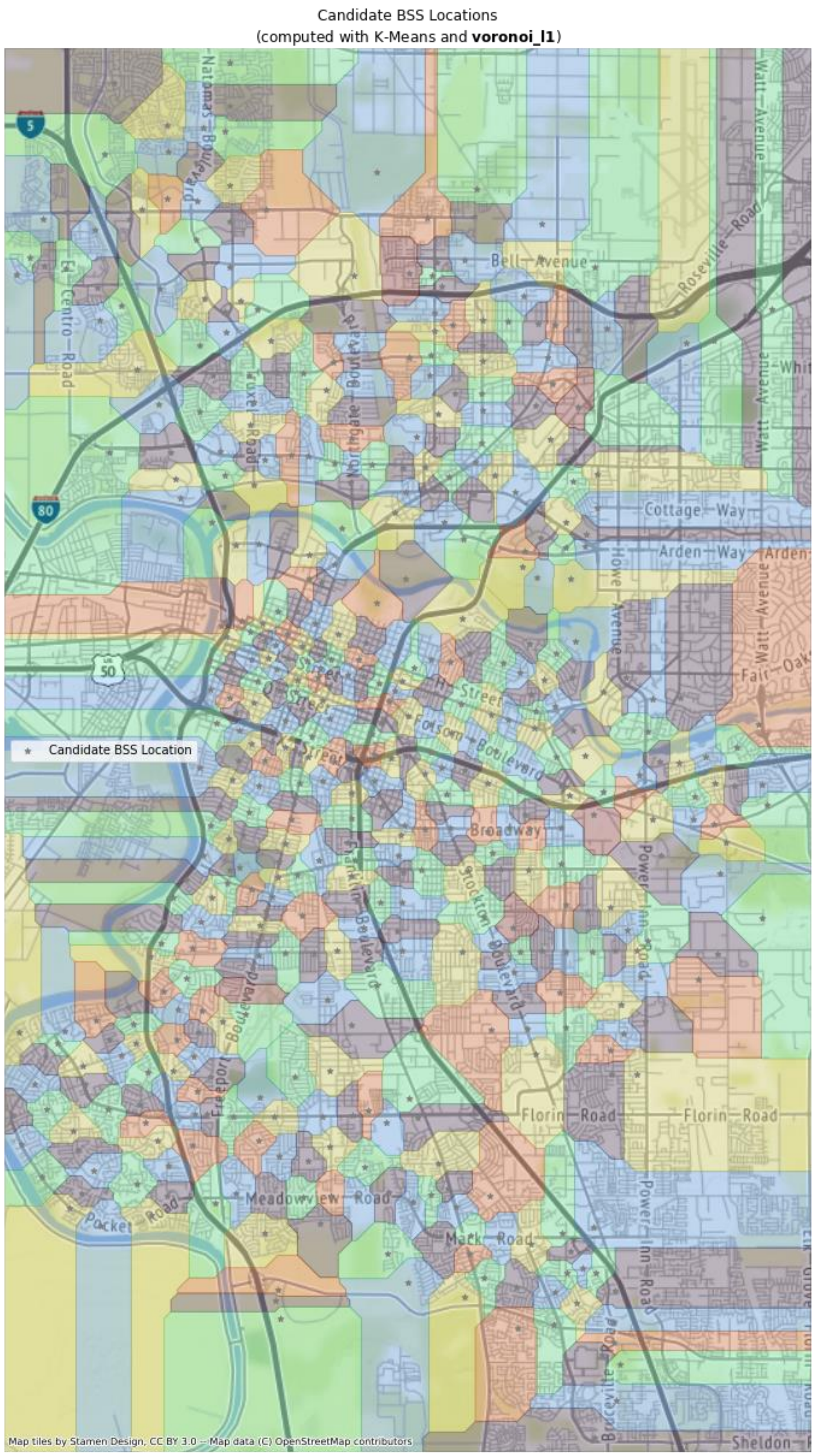


Figure 10. Candidate BSS locations

Genetic Algorithm

The BSS location problem is NP-hard, which can hardly be solved by enumerating all possible solutions to obtain the optimal objective function value. Given a large set of candidate facility locations, there could be a combination of possible solutions, while most of them return high impedances. It would take a very long time to traverse all the solutions, so we propose to use a heuristic algorithm to find the approximate optimal solution.

Among the heuristic algorithms, we use GA to search for optimal objective function values, which is a computational model of biological evolutionary process that simulates the natural selection and genetics mechanism of biological evolution, and is a method to search for optimal solutions by simulating the natural evolutionary process (Mirjalili 2019). Compared to other algorithms, the main features of GA are: 1) the direct operation on structural objects without derivation and function continuity; 2) the inherent implicit parallelism and better global search capability; 3) the probabilistic search method, which can automatically obtain and guide the optimized search space without defined rules, and 4) adaptive search direction. The basic steps are summarized as follows:

i. Randomly initialize the population (sized 50) which includes a series of initial solutions of BSS locations.
ii. Compute the fitness (objective function value) of solutions in the population according to whether it meets the optimization criterion, if it does, output the best individual and its optimal solution, and end. Otherwise, proceed to step iii.
iii. Select parents based on fitness, individuals with high fitness have a high probability of being selected and those with low fitness are eliminated.
iv. The chromosomes (part of independent variables) of the parents are crossed according to a certain method to generate offspring.
v. The chromosomes of the offspring are mutated.
vi. Generate a new generation of population (updated solutions) from crossover and mutation and return to step ii until 100 generations (i.e., iterations) are reached.

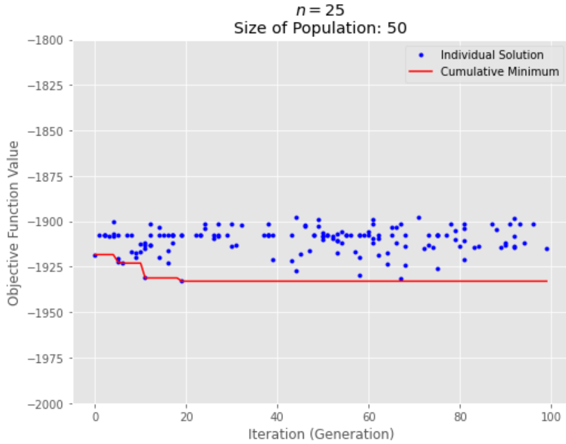
Results and Discussion

In this section, we leverage a genetic-algorithm-based multimodal ABM simulation framework to solve the BSS location optimization problem and present the results including 1) the BSS location optimization using genetic algorithm, and 2) POI accessibility improvements. We use four different settings with their corresponding numbers of BSS (denoted by n) in the optimization problem, namely 25, 50, 75 and 100. Under these four different settings, we expect to compare the spatial distribution patterns (i.e., layout or allocation in the city) of BSS and the accessibility improvement of bikeshare to the travel demand of AHC residents simulated in the ABM framework. From the simulation results, we also extract and summarize several key findings and policy implications.

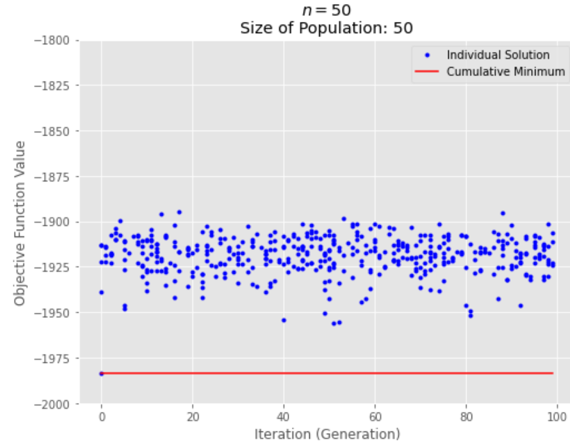
BSS Location Optimization Using Genetic Algorithm

As mentioned, we implement the simulation framework under four different BSS number settings. Specifically, the genetic algorithm is leveraged to solve for minimum objective function value. The objective function can be described as minimizing the total time saved by bikeshare with its introduction in the city, which means that the optimization problem is to compute the pairwise travel time difference between walk and bike modes, as well as transit and transit and bike modes. For example, in the ABM simulation model, for each resident we have four modes with different travel time, and when the transit or transit and bike mode is selected by the current resident, the difference (with negative sign) between these two modes of travel time is calculated and the total time saved by bikeshare for all residents is used as the objective function value.

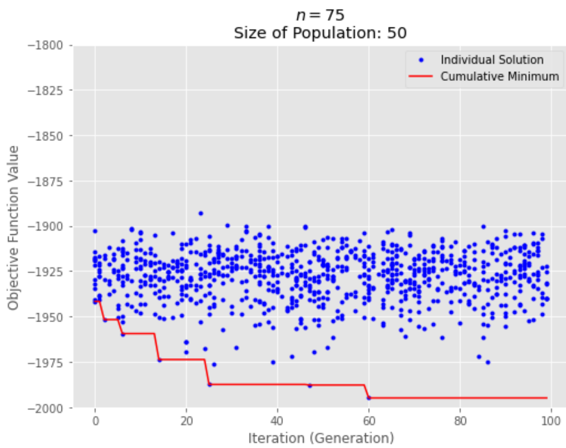
The parameters of the genetic algorithm are consistent for the four different BSS number settings. The population size is set to be 50, which means 50 viable solutions are computed for their corresponding objective function values. The probability of mutation is 0.5 to reach faster convergence for the algorithm. The number of generations (i.e., iterations) is 100, which means that a total of 5,000 times of an ABM model runs are performed for every BSS number setting. We select the best individual with the minimum objective function value among the 5,000 solutions when a GA-ABM simulation model is finished. Figure 11 shows the cumulative minimum objective function value under the four different settings of BSS number (denoted by n). In each of the settings, the number of agents simulated is set as 1,000, and is consistent for the ABM simulation models. With the four scatterplots in Figure 11, the smallest objective function value can be obtained for n=100. It is also found that when n is relatively small (its equal to 25 or 50), its convergence is slower due to the higher probability of mutation.



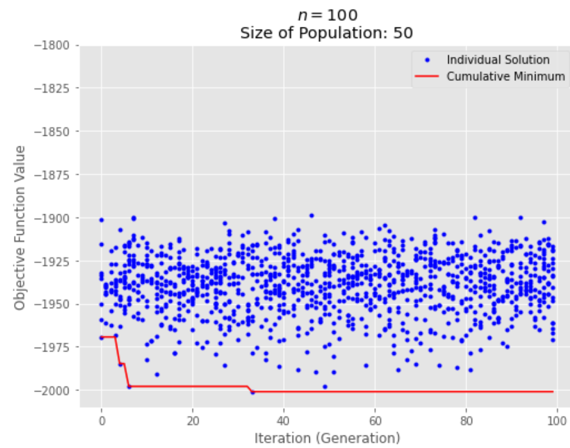
a) n=25



b) n=50



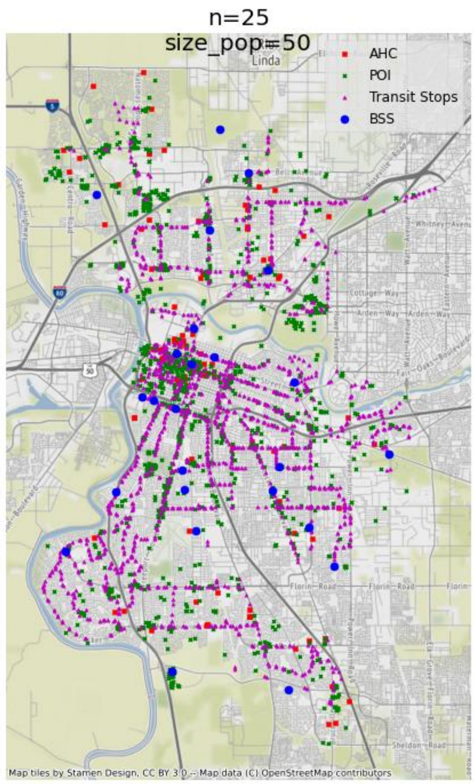
c) n=75



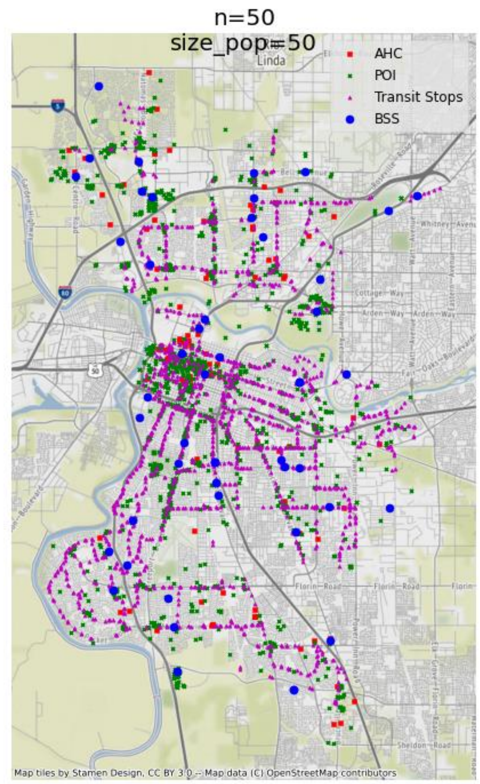
d) n=100

Figure 11. Cumulative minimum objective function values

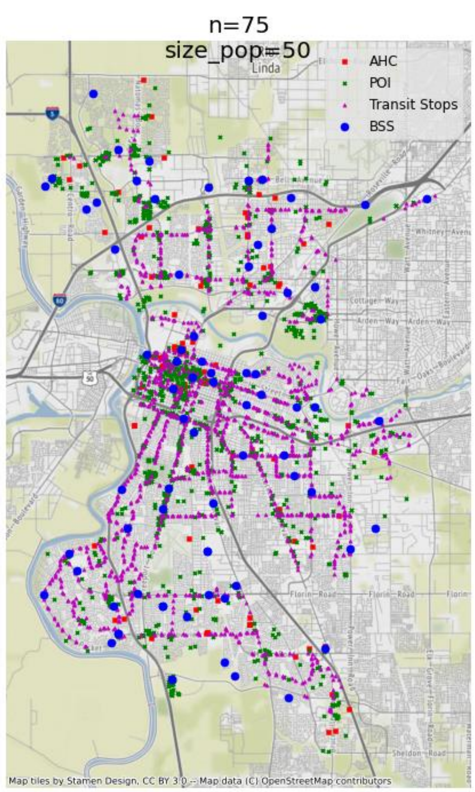
The simulation models under the four BSS number settings yield four different results of BSS locations (see the maps in Figure 12). When *n* is equal to 25 and 50, only a few BSSs are distributed in the downtown area, and most of them are distributed in the denser areas of POI and transit sites in the periphery of the city. In other words, when the number of BSSs is small, their connectivity with AHC is low. When the BSS increases to 100, its coverage to AHC increases significantly. Also, we find that there is no additive relationship between the four settings. That is, for example, the result of the setting at n=50 is not superimposed from the result of the setting at n=25, and this non-superimposed relationship makes the result of the genetic algorithm optimization more reliable. Also, when n=25, BSS is not sufficient for certain POI-dense areas in the city, such as Arden Fair, Natomas Center, and Sacramento State, among others. When policymakers focus more on accessibility equity, this setting is not preferable, though it saves cost from the planning and investment side.



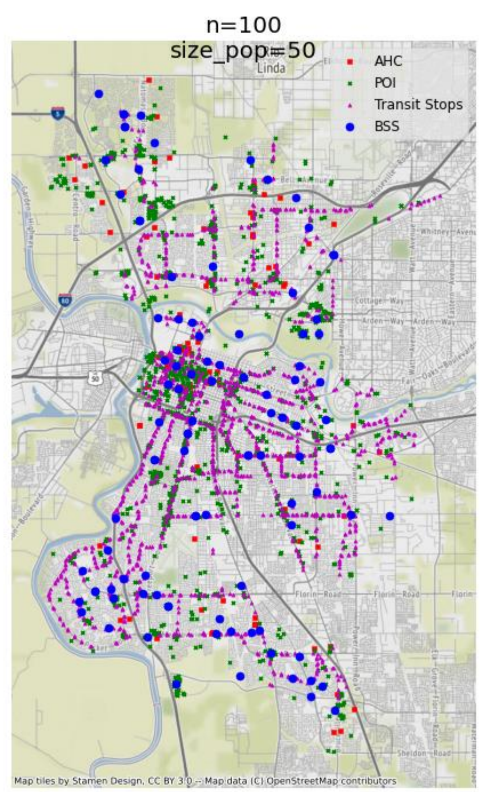
a) n=25



b) n=50



c) n=75



d) n=100

Figure 12. Optimized BSS locations under four station number settings

Mode Share

We consider analyzing the transportation mode shares by introducing bikeshare into Sacramento. Specifically, the results will cover the mode share of the four different travel modes, namely walk, bikeshare, transit and walk, and transit and bikeshare, and the average travel time in minutes. Trip purposes can affect travel distance because distinct types of trips tend to have different distances. For example, a trip to work is likely to be a longer distance than a trip to the grocery store, which is located closer to home. Similarly, a leisure trip to a distant vacation destination is likely to be longer than a trip to a nearby park.

Table 2 contains count of agents on the purpose of a trip and the mode of transportation used for that trip. There are five different settings of bikeshare stations indicated in the "BSS" column: 0, 25, 50, 75, and 100. The "Walk," "Bikeshare," "Transit+Walk," and "Transit+Bikeshare" columns show the number of agents who took a trip for each purpose and mode of transportation. There are three different purposes listed in the table: work, recreation, and shopping/eating out. It appears that the availability of BSS has a significant effect on the mode of transportation used for trips taken for different purposes. For trips taken for work purposes, the number of agents who took a trip using bikeshare or transit and bikeshare increases as the number of BSS increases. However, the number of agents who took a trip using walking or transit and walking increases as the number of bikeshare stations decreases. For trips taken for recreation and shopping/eating out purposes, similar patterns are obtained. Overall, it seems that the availability of BSS has a positive effect on the use of bikeshare and transit and bikeshare modes for trips taken for all three purposes.

Table 2. Mode share vs. BSS number across different trip purposes.

Purpose	BSS number	Walk	Bikeshare	Transit+Walk	Transit+Bikeshare
Work	n=0	29	0	469	0
	n=25	19	27	415	23
	n=50	18	50	409	20
	n=75	12	46	403	36
	n=100	11	77	368	44
Recreation	n=0	26	0	140	0
	n=25	32	6	147	11
	n=50	22	3	138	7
	n=75	27	29	113	8
	n=100	30	28	114	12
Shopping/eating out	n=0	113	0	83	0
	n=25	95	1	101	3
	n=50	124	2	75	10
	n=75	100	6	80	3
	n=100	86	17	85	6

Table 3. Average travel time of chosen modes vs. BSS number across different trip purposes.

Purpose	BSS number	Walk	Bikeshare	Transit+Walk	Transit+Bikeshare
Work	0	147.0		51.4	
	25	29.7	77.9	53.1	53.9
	50	21.5	67.4	50.6	53.8
	75	29.3	65.6	51.7	49.3
	100	22.9	57.9	51.0	54.1
Recreation	0	17.8		27.7	
	25	12.4	41.0	28.1	19.4
	50	11.4	36.7	28.8	27.8
	75	8.9	29.2	24.8	24.4
	100	9.5	33.4	26.4	26.8
Shopping/eating out	0	10.1		17.7	
	25	10.5	15.0	17.6	21.0
	50	8.9	30.9	16.9	19.7
	75	9.3	31.0	16.3	15.1
	100	7.2	24.1	15.2	16.6

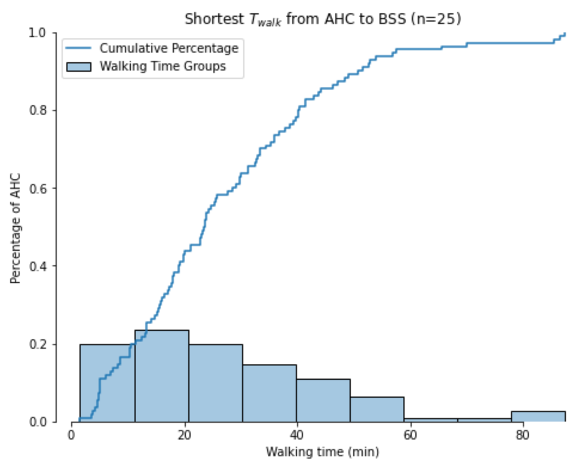
Table 3 shows the average travel time of different modes of transportation for different trip purposes (work, recreation, shopping/eating out) across different numbers of BSS in the area. The modes of transportation listed are walking, bikesharing, and using transit in combination with walking or bikesharing. The average travel times are in minutes. For example, for a work trip, with no BSS in the area, the average travel time by walking is 147.0 minutes. With 100 BSSs in the area, the average travel time by transit and bikesharing is 54.1 minutes.

The average travel time for walking decreases as the number of BSS increases for trip purposes of work and shopping/eating out. However, for the trip purpose of recreation, there is no clear trend in the travel times for walking as the number of BSS increases. There are a few potential reasons why the average travel time for walking might decrease as the number of BSS increases. One possibility is that as the number of BSS increases, people may be more likely to use bikesharing as a mode of transportation for shorter trips, which could reduce the number of people walking for those trips. Another possibility is that an increase in the number of BSS could lead to an increase in the number of bike lanes or other infrastructure that is conducive to biking, which could make it easier and faster for people to walk to their destination. It is also worth noting that Table 3 only presents average travel times, and there may be other factors that contribute to changes in travel time that are not captured in the simulated results.

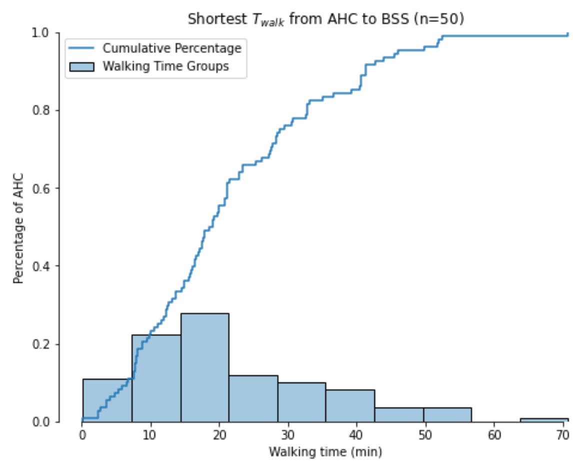
Accessibility Improvement

Four separate ABM single runs are performed with the four settings of the optimized BSS locations. The results yield the individual travel times of all 2,000 residents simulated in the ABM model. Figure 13 shows the walking time to reach the nearest BSS under the four different

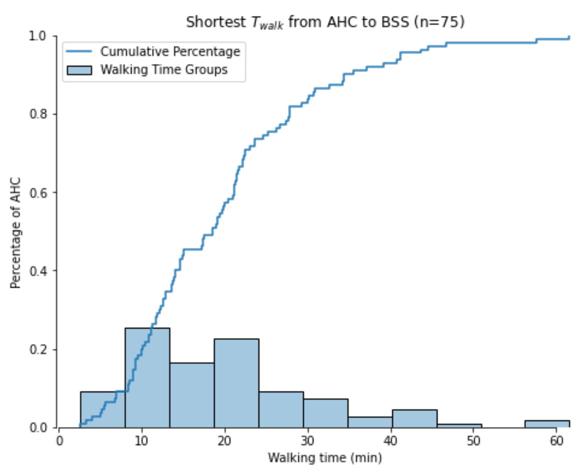
BSS number settings. Around 60% of AHC are approximately within 25, 21, 20 and 15 min of walking time from BSS as the n ranges from 25 to 100, respectively. A small portion of AHCs is out of the 60 min walking time radius when the number of stations is less than 100. In fact, the results in Figure 13 suggest that when n is less than 100, the coverage to AHC remains somehow consistent. Combining the results shown in Figure 12 (the BSS optimized location maps), we can see the addition of n from 25 to 75 is mostly improving the coverage to POI and transit stops, which means that the improvements in the accessibility of AHC residents are more reflected on the destination and transit connection sides, whereas we see little improvements on the trip origin side.



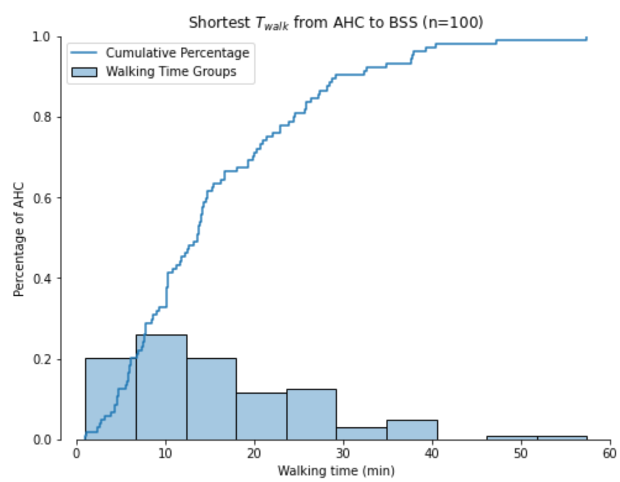
a) n=25



b) n=50



c) n=75



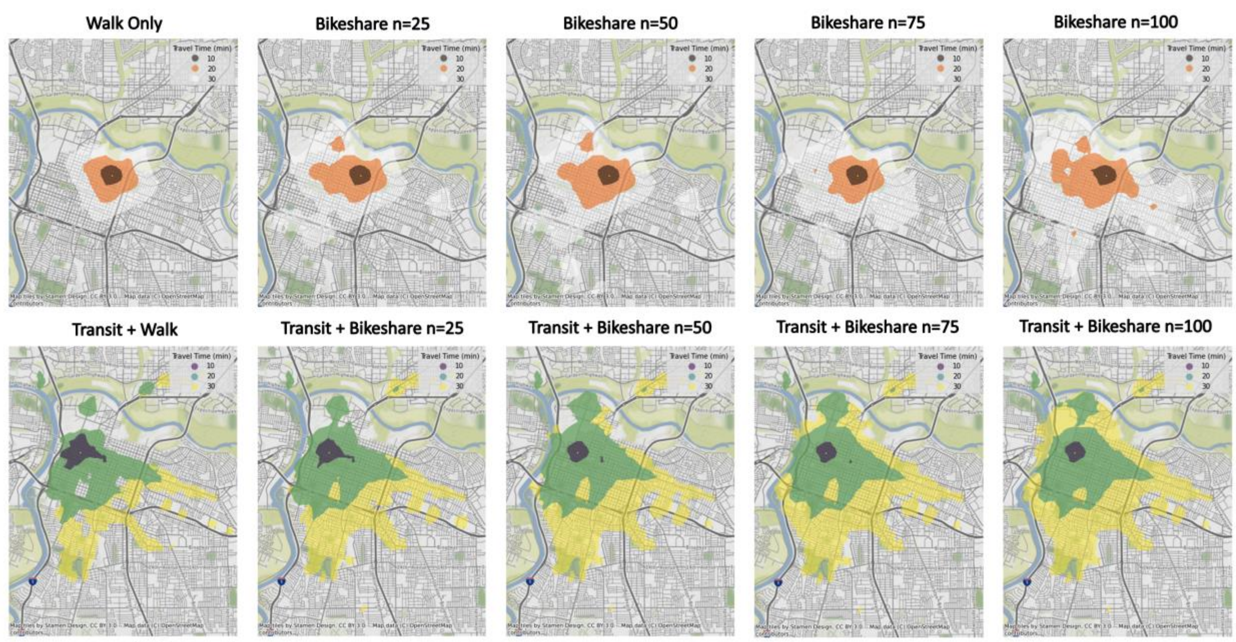
d) n=100

Figure 13. Shortest walking time to BSS from AHC

Apart from that, we measure the POI accessibility of both transit and walking and transit and bikeshare travel modes in different time ranges, namely 10 min, 20min and 30min. The POI accessibility is measured by the number of POIs that can be reached during a given travel time for the two travel modes. Table 4 shows the average counts of accessible POIs within specific time ranges for all the AHC in Sacramento under the four different BSS number settings. The results show that when the number of BSS is 25, the average POI count that can be accessed within 10 min, 20 min and 30 min, by the mode of transit and bike boosted by 4.9%, 30.3% and 10.4%, respectively, compared to the mode of transit and walk, which is not a significant effect. However, when n is equal to 100, this count for the three travel time ranges is boosted by 20.7%, 78.2% and 69.7% respectively. That is, the introduction of bikeshare significantly improves the accessibility of POIs through the strengthened connection of transit services and BSS.

Table 4. Average counts of accessible POI for different time ranges and BSS number settings

Mode		Travel Time Range		
		10 min	20 min	30 min
Transit+Walk		30.4	133.5	320.7
Transit+Bike	n=25	31.9	173.9	354.1
	n=50	34.6	204.2	457.8
	n=75	35.5	228.0	514.0
	n=100	36.7	237.9	544.2



- Top row: Bikeshare only
- Bottom row: Transit + bikeshare

Figure 14. Example of the accessibility isochrones of an AHC

Figure 14 shows the change in accessibility to two AHCs, as examples, in Sacramento with the introduction of BSS. The figure shows that the accessibility of the AHC improves significantly with the introduction of BSS. One probable reason for this improvement is the increased number of transportation options available to individuals living in the AHC. With the introduction of BSS, residents may have the option to bike to their destinations, which can be faster and more convenient than other modes of transportation, especially for shorter trips. In addition, the combination of bikeshare and transit may allow for even greater accessibility, as it may enable individuals to cover longer distances or access destinations that may not be directly served by either mode of transportation alone. Another possible reason for the improvement in accessibility is the increased connectivity provided by BSS. The presence of BSS may enable individuals to transfer between different modes of transportation more easily, such as biking to a nearby transit station or vice versa. This increased connectivity may make it easier for individuals to reach a wider range of destinations within a given time period. Overall, the introduction of BSS appears to significantly improve the accessibility of the AHC in Sacramento by providing additional transportation options and increasing connectivity.

Discussion and Recommendations

From the above results of solving the BSS location optimization problem, we provide a detailed discussion based on the key findings from the results and yield planning recommendations.

Key Findings

Multi-modal ABM simulation framework enables more realistic accessibility measurements

This project has made a methodological innovation for BSS location optimization. For simulating individual trips in the ABM simulation framework, we use OTP for multimodal route planning, which relies on the OpenStreetMap road network, GTFS bus network, and custom BSS network. This means that all travel modes of an individual necessarily include walking. The goal of this project is to reduce the travel time and access distance of individuals through bikeshare, which is also the goal of the BSS location optimization problem solved above. Unlike previous studies, which usually assume that individuals can achieve door-to-door accessibility using bikeshare services, the consideration of walking makes the simulation results in this work closer to reality and more relevant for policy and planning level reference.

Achieving maximum accessibility benefits by minimizing the number of BSS through the multimodal ABM simulation framework

This project aims to propose an ABM simulation framework to optimize the spatial distribution of BSSs given a fixed number of individual trips, and to find the combination of BSS locations that optimizes the objective function. By introducing bikeshare, the gap between affordable housing units and transit services is reduced, thus expanding the accessibility to its residents. The simulation results show that when n=100, the average count of POI included in the 30-minute travel circle of AHC residents increases by around 70%. This indicates that the number of BSS can be controlled at about 100 to improve the accessibility of AHC residents in Sacramento.

Different BSS configurations are needed for short- and long-distance trips

We found in the location optimization results of the four BSS number settings that the BSS distribution in the Downtown Sacramento area is less, yet the POI density in this area is higher than the surrounding areas. We believe that the sparse number of BSS limits the possibility of planning more BSSs in this area to increase the density and coverage. In fact, many trips in this area can be solved by walking. If we want to increase the share of bikeshare use in the POI-dense area, there is a further need to divide the trips by distance, exclude part of the inherent long-distance travel demand, and further optimize the BSS station layout for the remaining short-distance travel demand.

Planning Recommendations

From the above results of BSS location optimization, we have two recommendations for planning development, affordable housing planning and public transit planning.

To successfully implement bikeshare in affordable housing communities (AHCs) and increase accessibility to job, recreational, healthcare, and other destinations, it is important to understand the travel behavior and preferred destinations of AHC residents. To gather this information, we recommend conducting a travel survey for the residents of AHCs to study their trip purposes and destination choices. The results of this survey can help differentiate everyone's destination choice set, making the layout of BSS more responsive to real travel needs.

Moreover, in order to create and maintain good bike infrastructure, especially in suburban areas where setting up BSS may be more challenging, it is important to raise awareness among AHC residents about the maintenance and protection of bikeshare infrastructure. To achieve this goal, we suggest using financial incentive programs and community outreach programs as tools. These programs can help create and maintain good bike infrastructure in these regions and encourage the use of bikeshare services among AHC residents.

Conclusions

Through this research project we aimed to investigate the feasibility of using bikeshare services to bridge the gap between Affordable Housing Communities and transit services to help improve accessibility of the residents to different points of interest like healthcare, restaurants, or recreational destinations. Further we aimed to find optimal number and locations of Bike share stations to ensure maximum accessibility.

We achieved both these objectives by solving an optimization problem using a multi modal ABM- based simulation framework with the objective of minimizing the total travel time by introducing bike share stations in the network. This ABM based simulation is used to run the three stages of travel demand modelling: trip generation, trip distribution and mode choice to find the travel time difference when the mode choice is transit, walk and transit and bike and transit for 1000 residents. This ABM-based model is nested with a genetic algorithm framework which is used to find optimal locations for bike share stations. The ABM model is run four times for 25, 50, 75 and 100 bike share stations and the corresponding optimal locations, travel time savings and the resultant accessibility improvements were visualized.

The results of the optimization and ABM- based simulation indicated that the share of bike and bike & transit trips in the network. However, the share of bike and transit trips alone aren't significant till at least 100 BSS are introduced into the simulation. Additionally, we found that about 60% of the AHCs are within 25 min radius by walking when the number of stations range from 25 to 75. But when the number of stations is increased to 100 most AHCs are within 40 mins of walking distance and all of them are less than an hour away by walking.

Therefore, based on our results we can conclude that using a multimodal ABM simulation framework helps us to measure accessibility more realistically than when compared to using a single mode for measuring accessibility. Secondly, this methodology helps us to arrive at the minimum number of BSS necessary to maximize coverage. In our current analysis for the city of Sacramento, introducing 100 BSS increases the POI coverage from AHCs improves by 70% when a 30 min travel radius is considered. Finally, we conclude that we must consider short-distance travel demand and long-distance travel demand separately in the algorithm to introduce bike share services for shorter trips in relatively denser areas like downtown Sacramento. If we don't do so, most of the BSS will be located in suburban regions to support longer trips since the shorter ones can be covered by walking.

Three major recommendations for the successful implementation of bikeshare service would be: 1) conducting a periodic travel survey for the residents of AHCs to get an understanding of an individual's destination preferences for different purposes thus enabling us to improve the AMB framework to better simulate the actual travel patterns; 2) introducing programs to increase awareness of the use of bikeshare services in suburban regions and financial incentive programs to establish and maintain bike infrastructure in these areas; 3) surveying bike infrastructures to understand how affordable housing community residents feel comfortable when cycling on them.

The lack of detailed and thorough data on number of affordable housing units and their distribution by type of housing (studio/ 2 room/ 3 room …) proved to be a limitation for our analysis, since it made it difficult to estimate the population in AHCs for trip generation. We imputed the missing data (number of units in AHC) and then calculated the average size of a household in an AHC to estimate the population. The average size was calculated based on the assumption that the household size distribution in a AHC will be similar to that of the average of household size distributions in census block groups with more than 75 % low-income households. Additionally, the destinations for different residents were chosen based on the shortest distance from the AHC which doesn't reflect their actual travel pattern. These limitations can be tackled by using more accurate imputation techniques and using a travel survey to understand travel behavior of the residents respectively in future. Last, the future travel survey can also help us identify current transit routes used by AHCs. By comparing their current travel behaviors with transit and the predicted travel plans with bikeshare and transit, we can provide suggestions on future improvements on transit service, which can make the connection between transit and bikeshare seamless.

References

"Affordable Housing Policies: An Overview." 2016. Cornell Real Estate Review. May 24, 2016. https://blog.realestate.cornell.edu/2016/05/24/affordable-housing-policies-an-overview/.

Bills, Tierra S., and Andre L. Carrel. 2021. "Transit Accessibility Measurement Considering Behavioral Adaptations to Reliability." *Transportation Research Record* 2675 (5): 265–78. https://doi.org/10.1177/0361198120986567.

Boarnet, Marlon G., Raphael Bostic, Danielle Williams, Raul Santiago-Bartolomei, Seva Rodnyansky, Andy Eisenlohr, National Center for Sustainable Transportation, Davis University of California, and Los Angeles University of Southern California. 2017. "Affordable Housing in Transit-Oriented Developments: Impacts on Driving and Policy Approaches." CA17-2983. https://rosap.ntl.bts.gov/view/dot/32806.

Bryant Jr, James. 2013. "Finding the Optimal Locations for Bike Sharing Stations: A Case Study within the City of Richmond, Virginia."

Chandra, Shailesh, Muhammad Ehsanul Bari, Prem Chand Devarasetty, and Sharada Vadali. 2013. "Accessibility Evaluations of Feeder Transit Services." *Transportation Research Part A: Policy and Practice* 52 (June): 47–63. https://doi.org/10.1016/j.tra.2013.05.001.

Chen, Faan, Jiaorong Wu, Xiaohong Chen, and Jianjun Wang. 2017. "Vehicle Kilometers Traveled Reduction Impacts of Transit-Oriented Development: Evidence from Shanghai City." *Transportation Research Part D: Transport and Environment* 55 (August): 227–45. https://doi.org/10.1016/j.trd.2017.07.006.

Cheng, Shaowu, Bing Xie, Yiming Bie, Yaping Zhang, and Shen Zhang. 2018. "Measure Dynamic Individual Spatial-Temporal Accessibility by Public Transit: Integrating Time-Table and Passenger Departure Time." *Journal of Transport Geography* 66 (January): 235–47. https://doi.org/10.1016/j.jtrangeo.2017.12.005.

Croci, Edoardo, and Davide Rossi. 2014. "Optimizing the Position of Bike Sharing Stations. The Milan Case." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2461179.

CTCAC. 2021. "Multifamily Housing Projects - 2021." Tableau Software. 2021. https://public.tableau.com/views/MultifamilyHousingProjects-2021_16474710001300/Sheet1?:embed=y&:showVizHome=no&:host_url=https%3A%2F%2Fpublic.tableau.com%2F&:embed_code_version=3&:tabs=no&:toolbar=yes&:animate_transition=yes&:display_static_image=no&:display_spinner=no&:display_overlay=yes&:display_count=yes&:language=en-US&publish=yes&:loadOrderID=0.

Dawkins, Casey, and Rolf Moeckel. 2016. "Transit-Induced Gentrification: Who Will Stay, and Who Will Go?" *Housing Policy Debate*, April. https://www.tandfonline.com/doi/full/10.1080/10511482.2016.1138986.

García-Palomares, Juan Carlos, Javier Gutiérrez, and Marta Latorre. 2012. "Optimizing the Location of Stations in Bike-Sharing Programs: A GIS Approach." *Applied Geography* 35 (1): 235–46. https://doi.org/10.1016/j.apgeog.2012.07.002.

Griffin, Greg P., and Junfeng Jiao. 2018. "Crowdsourcing Bike Share Station Locations: Evaluating Participation and Placement." *Journal of the American Planning Association*, November, 1–13. https://doi.org/10.1080/01944363.2018.1476174.

Haughey, Rick, and Ryan Sherriff. 2011. "Challenges and Policy Options for Creating and Preserving Affordable Housing near Transit and in Other Location-Efficient Areas." https://www.urban.org/research/publication/challenges-and-policy-options-creating-and-preserving-affordable-housing-near-transit-and-other-location-efficient-areas.

Iacono, Michael, Kevin Krizek, and Ahmed M. El-Geneidy. 2008. "Access to Destinations: How Close Is Close Enough? Estimating Accurate Distance Decay Functions for Multiple Modes and Different Purposes." Report. Minnesota Department of Transportation. http://conservancy.umn.edu/handle/11299/151329.

Ibraeva, Anna, Gonçalo Homem de Almeida Correia, Cecília Silva, and António Pais Antunes. 2020. "Transit-Oriented Development: A Review of Research Achievements and Challenges." *Transportation Research Part A: Policy and Practice* 132 (February): 110–30. https://doi.org/10.1016/j.tra.2019.10.018.

Jahanshahi, Danial, Masoud Minaei, Omid Ali Kharazmi, and Foad Minaei. 2019. "Evaluation and Relocating Bicycle Sharing Stations in Mashhad City Using Multi-Criteria Analysis." *International Journal of Transportation Engineering* 6 (3): 265–83. https://doi.org/10.22119/ijte.2018.96377.1365.

Kimberlin, Sara. 2019. "California's Housing Affordability Crisis." https://calbudgetcenter.org/resources/californias-housing-affordability-crisis/.

LaMondia, Jeffrey J., Carey Blackmar, and Chandra R. Bhat. 2011. "Comparing Transit Accessibility Measures:A Case Study of Access to Healthcare Facilities." In . https://trid.trb.org/view/1092808.

Li, Wei, Qin Luo, Samwel Zephaniah, and Zhaoran Liu. 2020. "Evaluating the Dynamic Accessibility of Metro Systems in Overcrowded Conditions." *Transportation Research Record* 2674 (11): 42–52. https://doi.org/10.1177/0361198120941845.

Mirjalili, Seyedali. 2019. "Genetic Algorithm." In *Evolutionary Algorithms and Neural Networks: Theory and Applications*, edited by Seyedali Mirjalili, 43–55. Studies in Computational Intelligence. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-93025-1_4.

Nasri, Arefeh, and Lei Zhang. 2014. "The Analysis of Transit-Oriented Development (TOD) in Washington, D.C. and Baltimore Metropolitan Areas." *Transport Policy* 32 (March): 172–79. https://doi.org/10.1016/j.tranpol.2013.12.009.

"National Affordable Housing Act." n.d. Accessed October 15, 2022. https://www.hud.gov/sites/documents/NAHA215.TXT.

Nedwick, Todd, and Kimberly Burnett. 2015. "How Can the LIHTC Program Most Effectively Be Used To Provide Affordable Rental Housing Near Transit?" *Cityscape* 17 (2): 113–38.

OpenStreetMap. n.d. "Geofabrik Download Server." Accessed October 16, 2022. https://download.geofabrik.de/.

Polzin, Steven E., Ram M. Pendyala, and Sachin Navari. 2002. "Development of Time-of-Day–Based Transit Accessibility Analysis Tool." *Transportation Research Record* 1799 (1): 35–41. https://doi.org/10.3141/1799-05.

Qian, Xiaodong, and Miguel Jaller. 2020. "Bikesharing, Equity, and Disadvantaged Communities: A Case Study in Chicago." *Transportation Research Part A: Policy and Practice* 140 (October): 354–71. https://doi.org/10.1016/j.tra.2020.07.004.

———. 2021. "Bikeshare Destination Choices and Accessibility among Disadvantaged Communities." *Transportation Research Part D: Transport and Environment* 91 (February): 102686. https://doi.org/10.1016/j.trd.2020.102686.

Qian, Xiaodong, Miguel Jaller, and Giovanni Circella. 2022. "Equitable Distribution of Bikeshare Stations: An Optimization Approach." *Journal of Transport Geography* 98 (January): 103174. https://doi.org/10.1016/j.jtrangeo.2021.103174.

Qian, Xiaodong, and Deb Niemeier. 2019. "Identifying Bikeshare Station Locations to Improve Underserved Communities' Accessibility," August. https://doi.org/10.7922/G2NG4NVM.

Rybarczyk, Greg, and Changshan Wu. 2010. "Bicycle Facility Planning Using GIS and Multi-Criteria Decision Analysis." *Applied Geography* 30 (2): 282–93. https://doi.org/10.1016/j.apgeog.2009.08.005.

"SACRT GTFS - OpenMobilityData." n.d. Accessed October 16, 2022. https://transitfeeds.com/p/sacramento-regional-transit/67.

"Trip Purposes in U.S. Public Transit - Poll 2015." n.d. Statista. Accessed October 1, 2022. https://www.statista.com/statistics/715217/trip-purposes-in-us-public-transit/.

US Census Bureau. n.d. "American Community Survey 2016-2020 5-Year Data Release." Census.Gov. Accessed October 16, 2022. https://www.census.gov/newsroom/press-kits/2021/acs-5-year.html.

US Census Bureau for Economic Studies. n.d. "Longitudinal Employer-Household Dynamics." Accessed October 16, 2022. https://lehd.ces.census.gov/data/.

"U.S. Census Bureau QuickFacts: Sacramento City, California." n.d. Accessed October 10, 2022. https://www.census.gov/quickfacts/fact/table/sacramentocitycalifornia/PST045221.

Wang, Jenhung, Ching-Hui Tsai, and Pei-Chun Lin. 2016. "Applying Spatial-Temporal Analysis and Retail Location Theory to Public Bikes Site Selection in Taipei." *Transportation Research Part A: Policy and Practice* 94 (December): 45–61. https://doi.org/10.1016/j.tra.2016.08.025.

Welch, Timothy F. 2013. "Equity in Transport: The Distribution of Transit Access and Connectivity among Affordable Housing Units." *Transport Policy* 30 (November): 283–93. https://doi.org/10.1016/j.tranpol.2013.09.020.

Wuerzer, Thomas, Susan Mason, and Riley Youngerman. 2012. “Boise Bike Share Location Analysis,” 17.

Data Summary

Products of Research

The data used in this project for macroscopic statistical modeling include the following:

1. Affordable Housing Communities Data: This data includes information on the location and number of units in affordable housing projects in Sacramento. It is being used to study the impact of affordable housing on transportation patterns in the city. The data can be accessed at: [https://www.treasurer.ca.gov/ctcac/projects.asp; https://www.shra.org/other-affordable-housing-options/].
2. Demographic Information: This data includes population demographics such as household income and number of occupied and vacant housing units at the census block group level. It is being used to estimate the population of affordable housing communities and to study the impact of demographic factors on transportation patterns in Sacramento. The data can be accessed at: [https://data.census.gov/].
3. OpenStreetMap Road Network Data: This data includes information on the name, length, and class of roadway segments in Sacramento. It is being used to model transportation patterns in the city and to study the impact of affordable housing on transportation infrastructure. The data can be accessed at: [https://download.geofabrik.de/north-america/us/california.html].
4. Points of Interest Data: This data includes information on locations of various points of interest in Northern California. It is being used to study the impact of access to points of interest on transportation patterns in Sacramento. The data can be accessed at: [https://download.geofabrik.de/north-america/us/california.html].
5. General Transit Feed Specification Data: This data includes information on public transit schedules and routes in Sacramento. It is being used to model public transportation usage in the city and to study the impact of affordable housing on public transit usage. The data can be accessed at: [https://transitfeeds.com/p/sacramento-regional-transit/67; https://transitfeeds.com/p/sacramento-regional-transit/161].
6. Longitudinal Employer-Household Dynamics Data: This data includes origin-destination employment data for census blocks in Sacramento. It is being used to study the impact of employment patterns on transportation patterns in the city. The data can be accessed at: [https://lehd.ces.census.gov/data/].

Data Format and Content

The data used in the new project is likely to be in a variety of formats and may include both structured and unstructured data. Some of the data sources, such as the American Community Survey data and the Longitudinal Employer-Household Dynamics data, are likely to be provided in structured tabular formats such as .csv or .xlsx files. Other data sources, such as the OpenStreetMap data and Points of Interest data, may be provided in unstructured formats such as .xml or .json files. The content of the data will vary depending on the data source. For example, the Affordable Housing Communities Data may include information such as the location, number of units, and other details about affordable housing projects in Sacramento. The demographic information may include population demographics such as household income and number of occupied and vacant housing units at the census block group level. The OpenStreetMap data may include information on the name, length, and class of roadway segments in Sacramento, while the Points of Interest data may include information on the location and type of various points of interest in the region. The General Transit Feed Specification data may include information on public transit schedules and routes in Sacramento, and the Longitudinal Employer-Household Dynamics data may include origin-destination employment data for census blocks in the city.

Data Access and Sharing

The data used for this project is publicly available at https://doi.org/10.25338/B87P9Z, and no commitment is required from the companies. However, data use will follow the corresponding agencies' restrictions. The ABM simulation python codes are also available at https://doi.org/10.25338/B87P9Z—to replicate this study, users will need to download and run the code if they want to replicate the ABM simulation.

Reuse and Redistribution

The data used in this project is sourced from a variety of sources, each of which has its own terms of use and restrictions on reuse and redistribution. Users of the data are responsible for ensuring that they comply with the terms of use and any restrictions on reuse and redistribution of the data.

Some of the data sources, such as the American Community Survey and the Longitudinal Employer-Household Dynamics data, may be available for reuse and redistribution with proper attribution. Other data sources, such as the OpenStreetMap data and Points of Interest data, may have more restrictive terms of use that prohibit or limit reuse and redistribution.

In general, users of the data should carefully review the terms of use for each data source and ensure that they comply with all applicable restrictions on reuse and redistribution. Suggested citation information for each data source should be included in any publications or presentations that make use of the data. Also, users of the python code for ABM simulation should use the following suggested citation:

> Xiao, Runhua; Jaller, Miguel; Qian, Xiaodong; Joby, Raina (2023), Optimizing bikeshare service to connect affordable housing units with transit services, Dryad, Dataset, https://doi.org/10.25338/B87P9Z