Advancing Redwood City's Bicycle Infrastructure Through a Geodesign Workflow

by

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To my family, my friends, and my hometown

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Abbreviations

CAD	Computer-aided design
CAHPI	California Healthy Places Index
C/CAG	City/County Association of Governments
DEM	Digital Elevation Model
EPCs	Equity Priority Communities
GIS	Geographic information system
IRB	Institutional Review Board
MPH	Miles Per Hour
MTC	Metropolitan Transportation Commission
OSM	OpenStreetMap
SKP2OSM	SketchUp to OpenStreetMap Plug-In
US	United States
USC	University of Southern California
WBTI	Walk Bike Thrive Initiative

Abstract

In the United States, emission-releasing cars reign as the leading form of transportation among citizens. Given the increasing effects of global climate change, it is critical that society finds alternative solutions to travel. The use of geodesign, combining data-driven spatial analysis with thoughtful design and community input, shows promise as an approach to better design transportation infrastructure in the US. This thesis applies a geodesign methodology to propose biking infrastructure improvements in Redwood City, CA. It first assesses existing bikeability as of 2022 using a spatial analysis in a GIS. It finds that Redwood City has moderate bikeability with potential for improvements that if implemented, will simultaneously help solve issues related to economic, social, and transport inequity. The project next selects three specific street segments in the city that could most benefit from improved biking infrastructure. It makes the selection through a combined analysis of these bikeability results, assessments by local stakeholder organizations of underserved areas, and community feedback gathered at a public workshop organized by the author that focused on biking in the city. These three selected street segments underwent a design process, resulting in models and renderings of what improved cycling infrastructure could look like in Redwood City. This thesis ultimately serves as an exemplar methodology that can be applied to other cities in the US to increase local bikeability and improve long-term sustainability in terms of social equity and the environment.

Chapter 1 Introduction

Cycling is an efficient and sustainable method for humans to travel within a community, city, or region. However, American city planners and municipalities tend to focus less on implementing bicycle infrastructure and instead prioritize high-speed freeways, wide parkways, and sprawling parking lots. American car-dependency poses multiple challenges for residents, such as the high cost of car-ownership which burdens already-disadvantaged communities. Heavy reliance on cars also poses challenges for the environment through the release of large amounts of carbon dioxide and other greenhouse gases. In contrast, bike use is relatively inexpensive, correlates with improved physical and mental health, and releases no greenhouse gasses. Despite the obvious benefits of bike use, it is difficult to safely and consistently ride a bike to perform daily tasks in many cities across the United States (US). Biking to work or the grocery store is challenging because bicycle infrastructure is usually nonexistent, and what infrastructure does exist is often nothing more than a simple line of paint on the road which offers cyclists zero physical protection from passing cars. Also, many American communities lack the connectivity to form efficient cycling networks. Cycling as a form of transportation in the United States (US) can be improved by increasing bikeability, which is defined as "the extent to which an environment is convenient and safe for cycling" (Reggiani et al. 2022).

This thesis focuses on bikeability in Redwood City, CA. Redwood City is a small city in California's Silicon Valley with a government that is interested in improving biking infrastructure. As part of the city's Walk Bike Thrive Initiative (WBTI), a long-term plan for municipal urban improvements, the city has already proposed 132 cycling infrastructure improvement projects (referred to as "proposed projects" throughout this thesis). This thesis creates design concepts for three proposed projects. It selects these three by evaluating current bikeability across the city, considering the relationship between the proposed projects and social equity, and listening to community priorities in an author-led community workshop. The remainder of this chapter describes the research goals, the study area, a discussion of present-day cycling in Redwood City, and a summary of the project's motivation.

1.1 Research Goals

This thesis project leveraged a geodesign methodology, combining spatial analysis, stakeholder engagement, and urban design modeling to provide a roadmap for increasing Redwood City's bikeability.

The first goal of the project was to analyze and quantify bikeability in Redwood City. This was performed using a weighted sum calculation in a geographic information system (GIS) with six variables conducive to bikeability.

The second goal was to assess the city's WBTI proposed projects in terms of social equity. Each proposed project was evaluated in a GIS to calculate the extent to which it would benefit communities that have historically been underserved in terms of social and economic resources. This assessment leveraged the knowledge of four municipal stakeholder organizations that have previously identified underserved communities using a variety of demographic metrics, such as median household income and ethnicity.

The third goal was to involve Redwood City residents in the methodology and advancement of cycling in Redwood City. To do this, a workshop was held to gain insight from Redwood City residents and allow them to voice their concerns about the state of local bikeability in 2023 as well as their wishes for the future of local bikeability.

The fourth goal was to select three of the city's WBTI proposed projects to undergo a design process. The selections were made by combining the results of the first three components in a weighted sum calculation.

The fifth research goal was to create 3D designs of what improved infrastructure could look like for the three selected proposed projects. This was done using SketchUp, a 3D modeling software.

Overall, this project used a mixed-methods, interdisciplinary, and nonlinear approach to address Redwood City bikeability and provide valuable insight to city decision makers. The geodesign methodology used in this project can be applied to other cities where relevant and thorough spatial data can be acquired to support efforts to improve bicycle infrastructure. Increased bikeability across American cities will be a positive change for the environment and public health and will also reduce equity gaps.

1.2 Study Area

The study area for this thesis is Redwood City, CA (Figure 1. Redwood City, Californi). Redwood City is located in Silicon Valley on the San Francisco Bay Area Peninsula and is equidistant between San Francisco and San Jose. Redwood City is bordered by Atherton to the southeast, Woodside to the south, San Carlos to the northwest, and the unincorporated communities of North Fair Oaks to the east and Emerald Hills to the west. The official city boundary encompasses roughly 35 square miles, of which approximately half is marshland or San Francisco Bay water. The legal limits of Redwood City include the community of Redwood Shores, which is located about three miles northwest of downtown Redwood City. Redwood City is a suitable study area for a geodesign project focused on advancing bikeability because of its existing bike infrastructure, generally flat terrain, and government interest in improving the bike network.

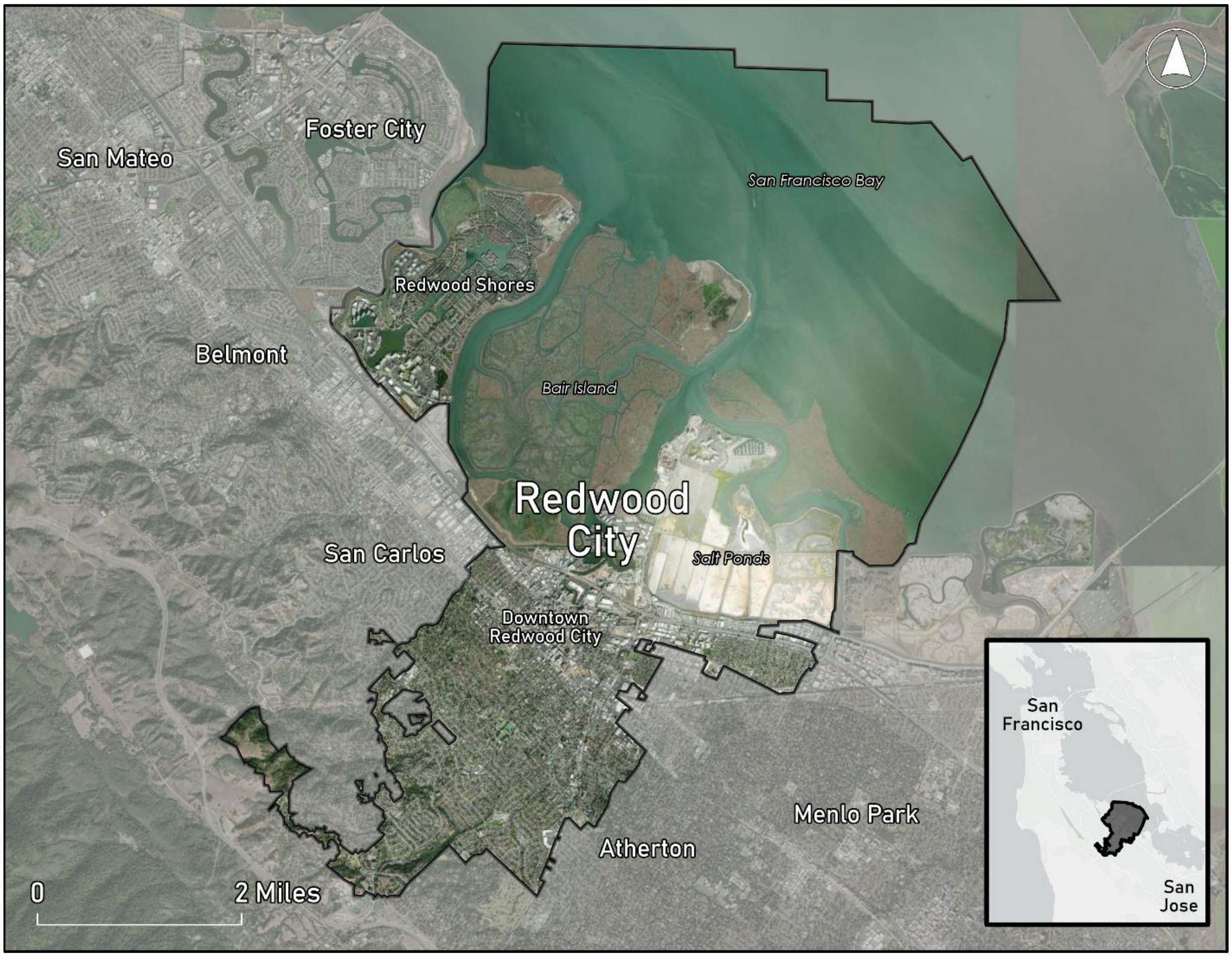


Figure 1. Redwood City, California

Following the tech boom of the late 1990s and the influx of businesses and residents to Silicon Valley, Redwood City grew into a denser and more diverse city. According to the US Census Bureau, the population of Redwood City was 84,518 in 2020. The residents live in a mix of single and multi-family homes, with a majority of dense housing being located in the following neighborhoods: Centennial, Downtown, Stambaugh-Heller, and Redwood Village (neighborhoods 11, 12, 14, and 15 in Figure 2. Redwood City neighborhoods). Much of the central, southern, and western areas of Redwood City feature suburban-style single family homes. It is worth noting that Redwood City's streets for the most part follow a grid-like structure. Cul-de-sacs, which are detrimental to bikeability, are rare. According to US Census data, approximately 41.1% of residents identify as White-non-Hispanic, 35.3% as Hispanic or Latino, and 16.3% as Asian (United States Census Bureau 2022). In 2022, the median household income was $134,287, and the poverty rate was 7.1% (United States Census Bureau 2022).

Redwood City is undergoing rapid change and growth and in April of 2023, was designated as a Prohousing Community by California Governor Gavin Newsom. California cities can apply to receive the Prohousing designation which if given, allows them to be eligible for funding and incentives conditioned on the construction of affordable and sustainable housing as well as updated infrastructure (California Department of Housing and Community Development n.d.). Redwood City is one of 22 Prohousing communities in California (Iracheta 2023).

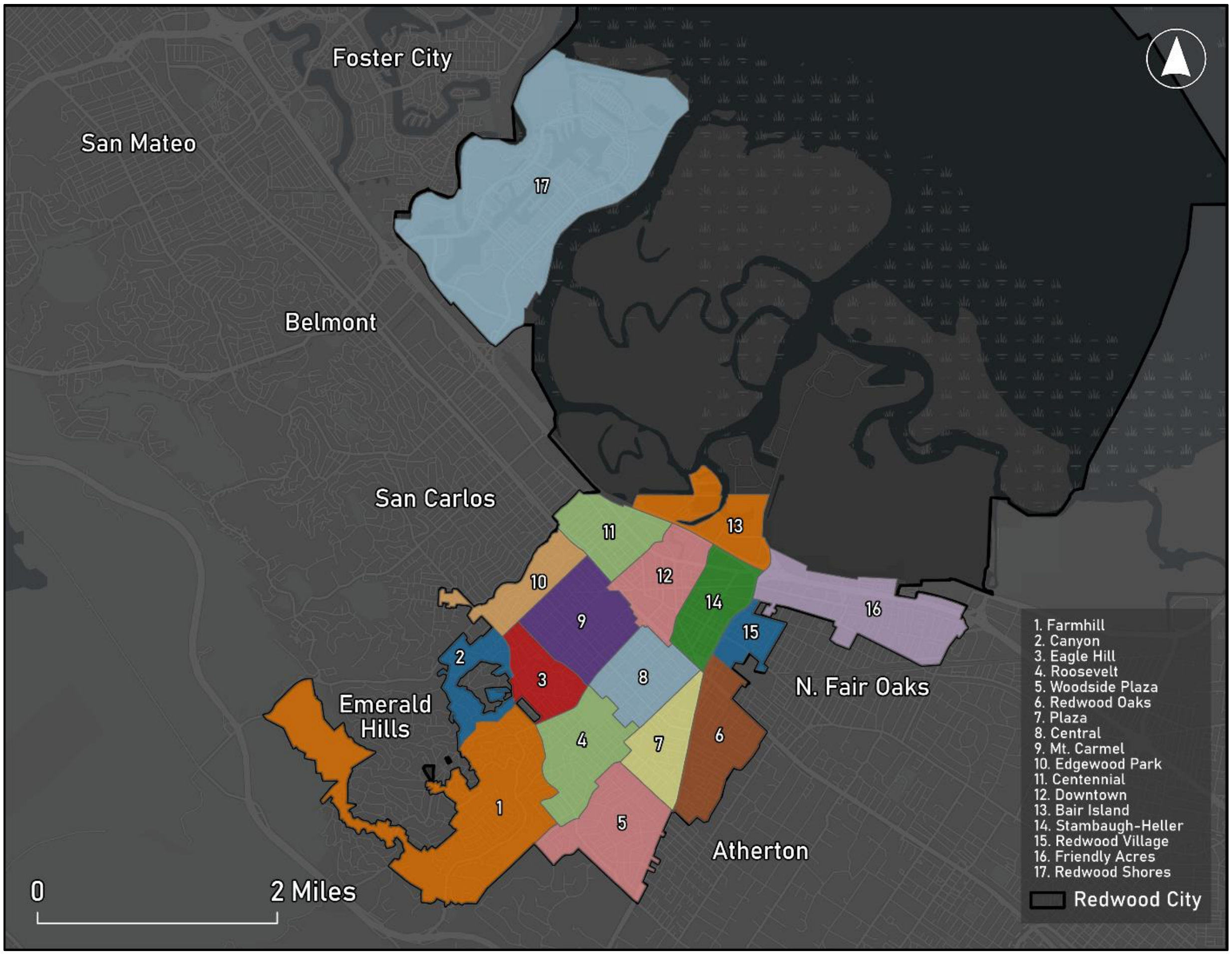


Figure 2. Redwood City neighborhoods

The terrain and urban layout of Redwood City make it naturally conducive to good bikeability. Much of the city is relatively flat, however as one travels further west, the terrain becomes hillier. Alameda de las Pulgas, a main arterial road that runs from the northwest to the southeast (see Figure 3. Redwood City arterial roads), generally acts as a border between flat land to the east, where a majority of residents live, and sloped land to the west. Downtown Redwood City, boxed in by El Camino Real, Chestnut Street, Veterans Boulevard, and Brewster Avenue (see Figure 3), is home to an abundance of dining, retail, and nightlife options and also serves as a hub for business headquarters, many of which are involved in the technology sector. The downtown area also features a CalTrain station, which offers rail connectivity between San

Francisco and San Jose, and a SamTrans bus depot, which offers bus connectivity within San Mateo County.

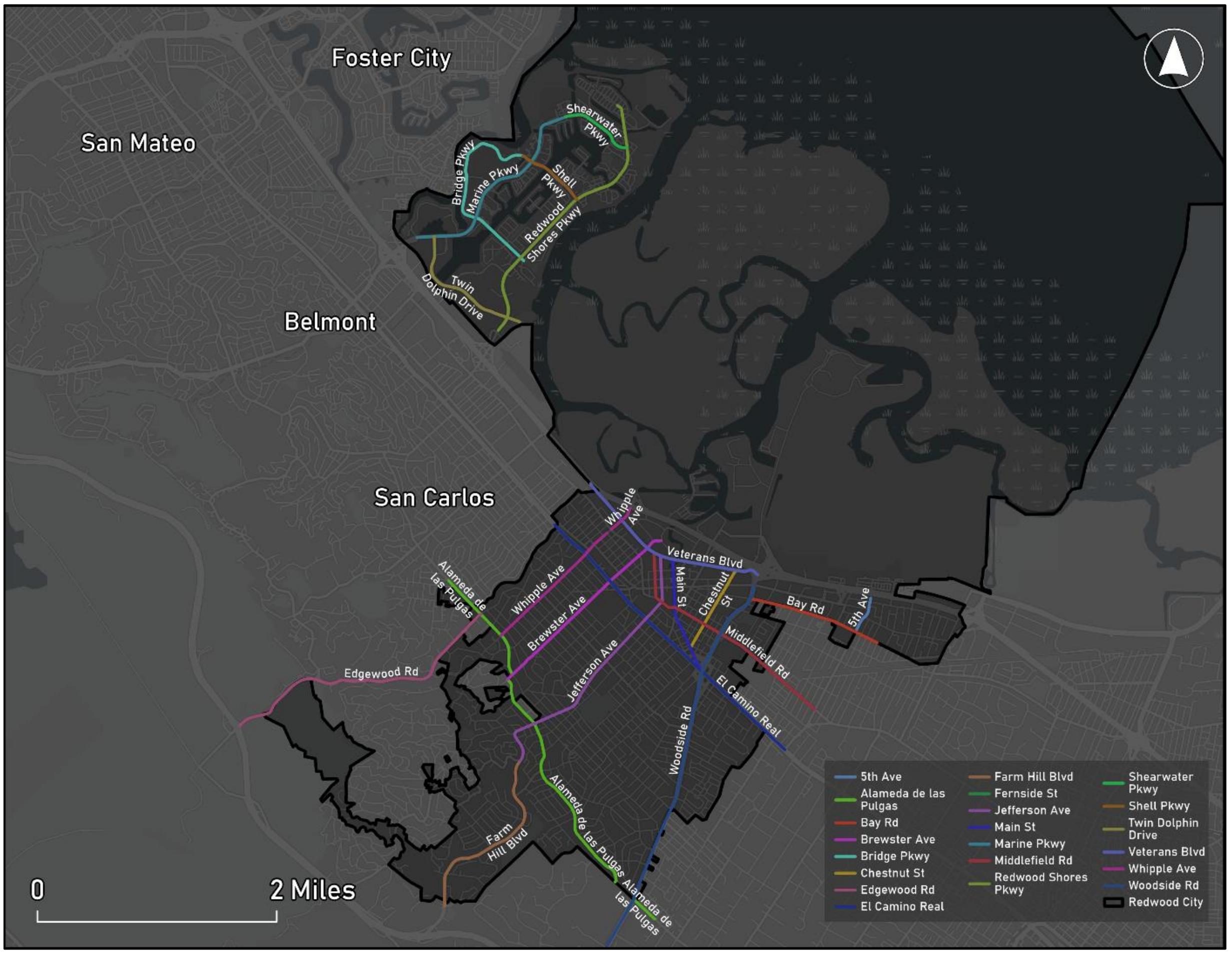


Figure 3. Redwood City arterial roads

1.3 Cycling in Redwood City

While Redwood City does maintain a significant cycling network, the current infrastructure is lackluster and does not provide safety or connectivity to cyclists. However, the city has expressed a desire to improve cycling and has outlined these goals in the WBTI.

1.3.1 Existing Cycling Conditions

As of 2023, Redwood City does have a cycling network (Figure 4). The existing bike lanes do not offer a high amount of connectivity and most of the infrastructure is made up of Class II and Class III bike lanes which offer no physical protection to the rider and are limited to painted markings on the street that indicate where cyclists should ride. Class I and Class IV bike lanes provide physical protection for cyclists, but they are not common in Redwood City and are not located in efficient places; they are generally located near the marshes and San Francisco Bay where they provide good bike infrastructure for leisure riding, but not for commuting.

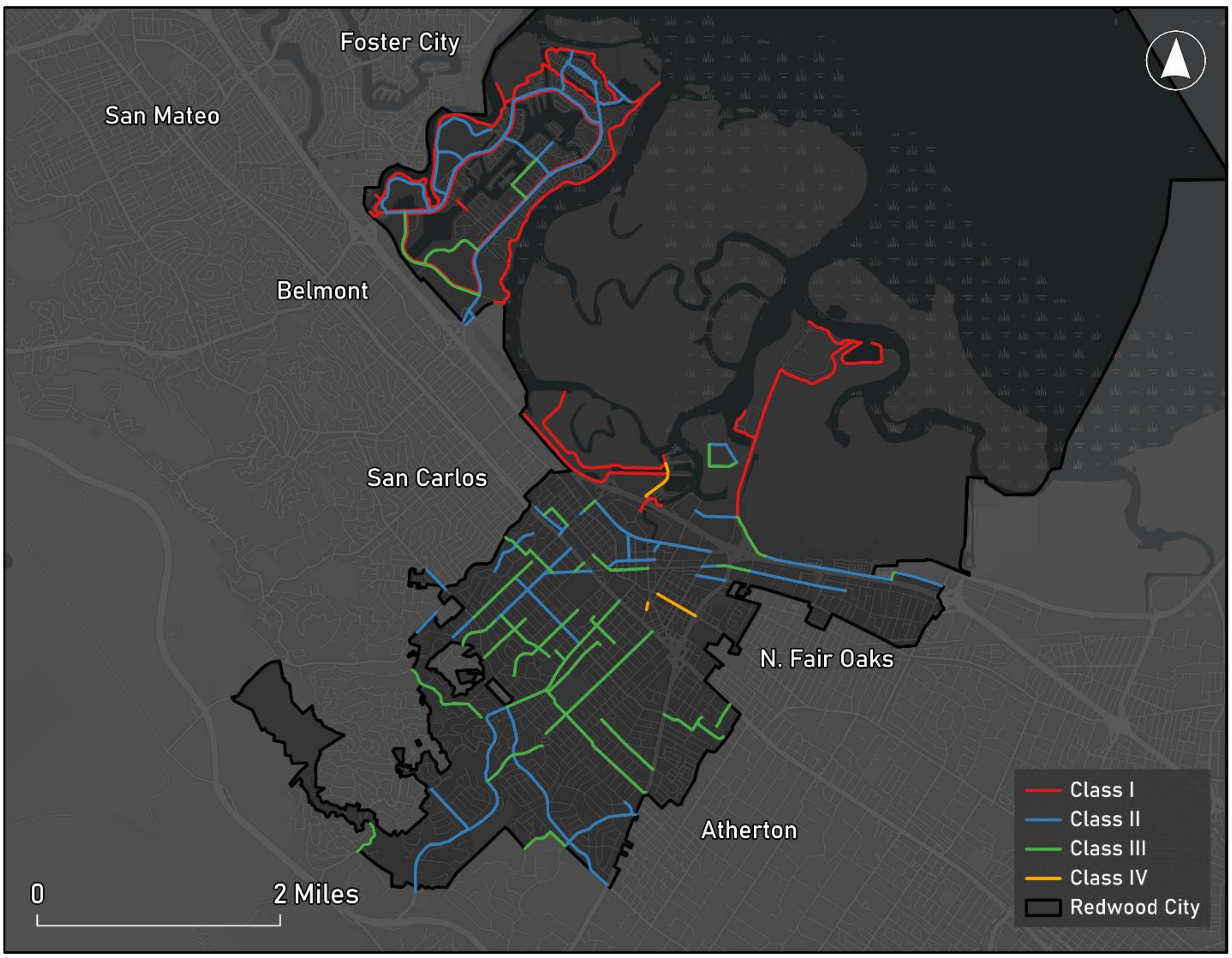


Figure 4. Existing bike lane network

Each instance of cycling infrastructure in Redwood City falls into one of four classes. Class I bike infrastructure refers to bike trails that are fully separated from traffic and in most cases, do not run parallel to roads (Figure 5, top left). The existing Class I lanes are concentrated along Redwood City's coast and support cycling as a form of recreation rather than transportation. Class II bike infrastructure refers to bike lanes that share roadways with cars but have their own space as indicated by painted white lanes and green lanes (Figure 5, top right). Class II bike lanes offer no physical protection for cyclists. Class III bike infrastructure are roads that have been designated as bike routes, but cyclists are expected to share the road with cars and do not have their own space (Figure 5, bottom left). Class III bike infrastructure offers no physical protection and the only indication that these roads are intended for bike use are the stenciled bike sharrows painted on the street. Class IV bike infrastructure refers to bike lanes that are fully separated from the street but run parallel to existing roads (Figure 5, bottom right). They offer ample physical protection for cyclists. Figure 5 shows an example of each of the four bike infrastructure classes in Redwood City.

Figure 5. Redwood City bike infrastructure classes

1.3.2 Walk Bike Thrive Initiative

In 2022, the city published the comprehensive WBTI, which aims to improve various physical aspects of the city and its infrastructure by developing policy to create a safe, walkable, and bikeable urban environment. The WBTI is a 263-page document that includes written plans, maps, and statistics. One of the primary targets of the initiative is to improve bikeability, which includes adding new bike lanes (Figure 6), creating bike boulevards which are physically separated from streets, adding additional bike parking near desirable destinations, and improving street connectivity. While this plan demonstrates the elected city officials' awareness of the utility of increased cycling in terms of public health and environmental sustainability, the physical infrastructure and policy must be crafted efficiently and effectively to prove meaningful and ultimately receive implementation.

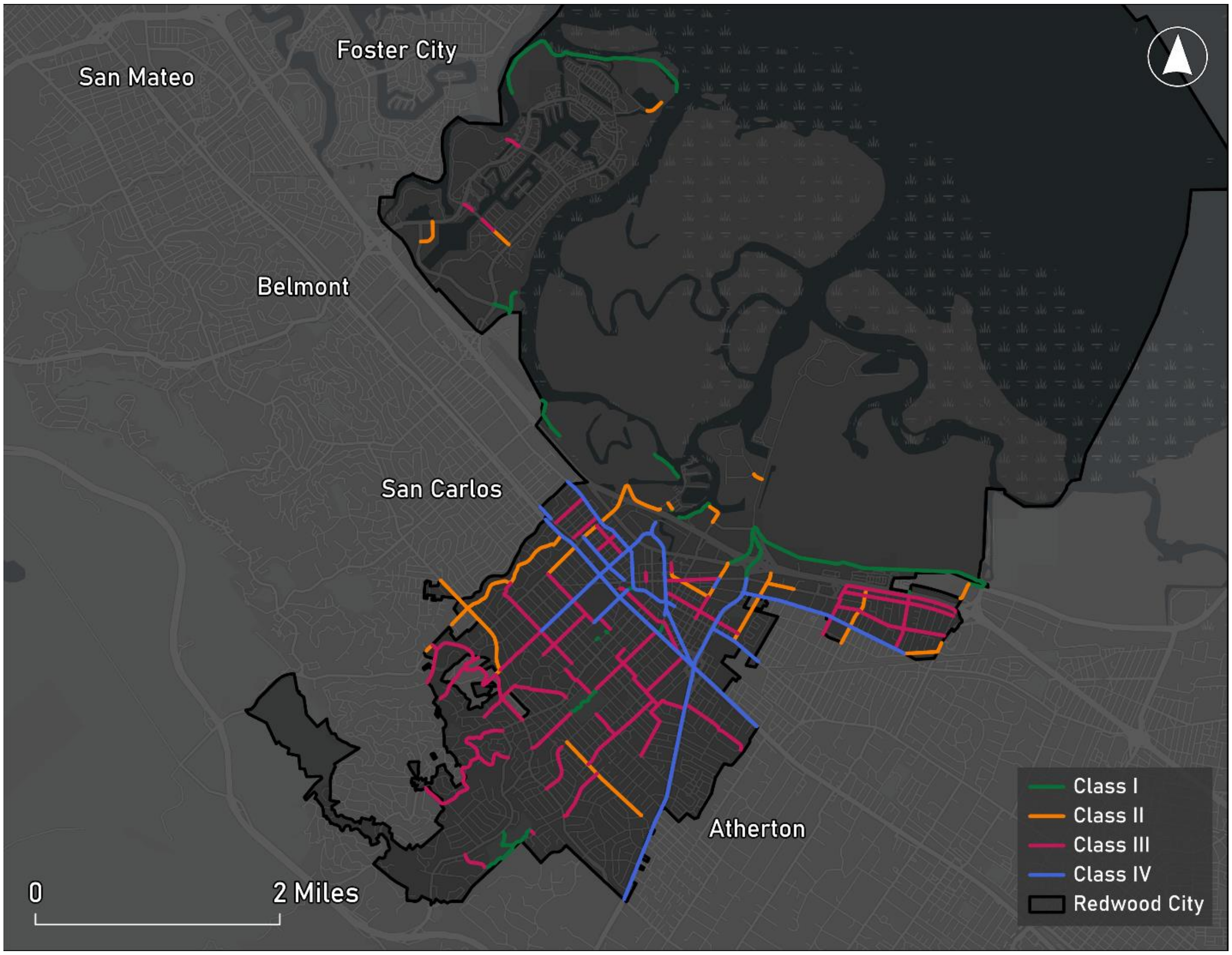


Figure 6. Proposed bike lane network

The city has made clear that the full implementation of the proposal is not guaranteed, and it is therefore critical that the most valuable proposed additions to the bike lane network are identified and prioritized. To identify these proposed projects, GIS has been used to assess the strength of bicycle infrastructure as it existed in 2022 and evaluate how future bike infrastructure may resolve issues related to the equal allocation of transportation resources to historically disadvantaged communities. Projects completed in communities that have been identified by stakeholders as being historically underserved and faced with equity issues generally have a higher likelihood of receiving regional and state funding. From a financial perspective, it is imperative that those projects are prioritized to maximize the number of infrastructure improvements made in the city, given the limited budget. The overall goal of this thesis project was to design and execute a methodology that could assist city staff and council members in their decision-making process for proposed projects listed in the WBTI, which would contribute to an advanced bike lane network. If the proposed projects are fully implemented, cycling connectivity would be high across the city and gaps in the current network would be filled, especially within the eastern half of the city. In addition, fully protected routes would protrude from downtown towards the southwest into the residential areas, making cycling a more attractive option for the city's residents (Figure 7). This thesis also directly supports one of the six main goals set by the WBTI: "Invest in projects that support a resilient, equitable, and sustainable transportation system" (City of Redwood City 2022).

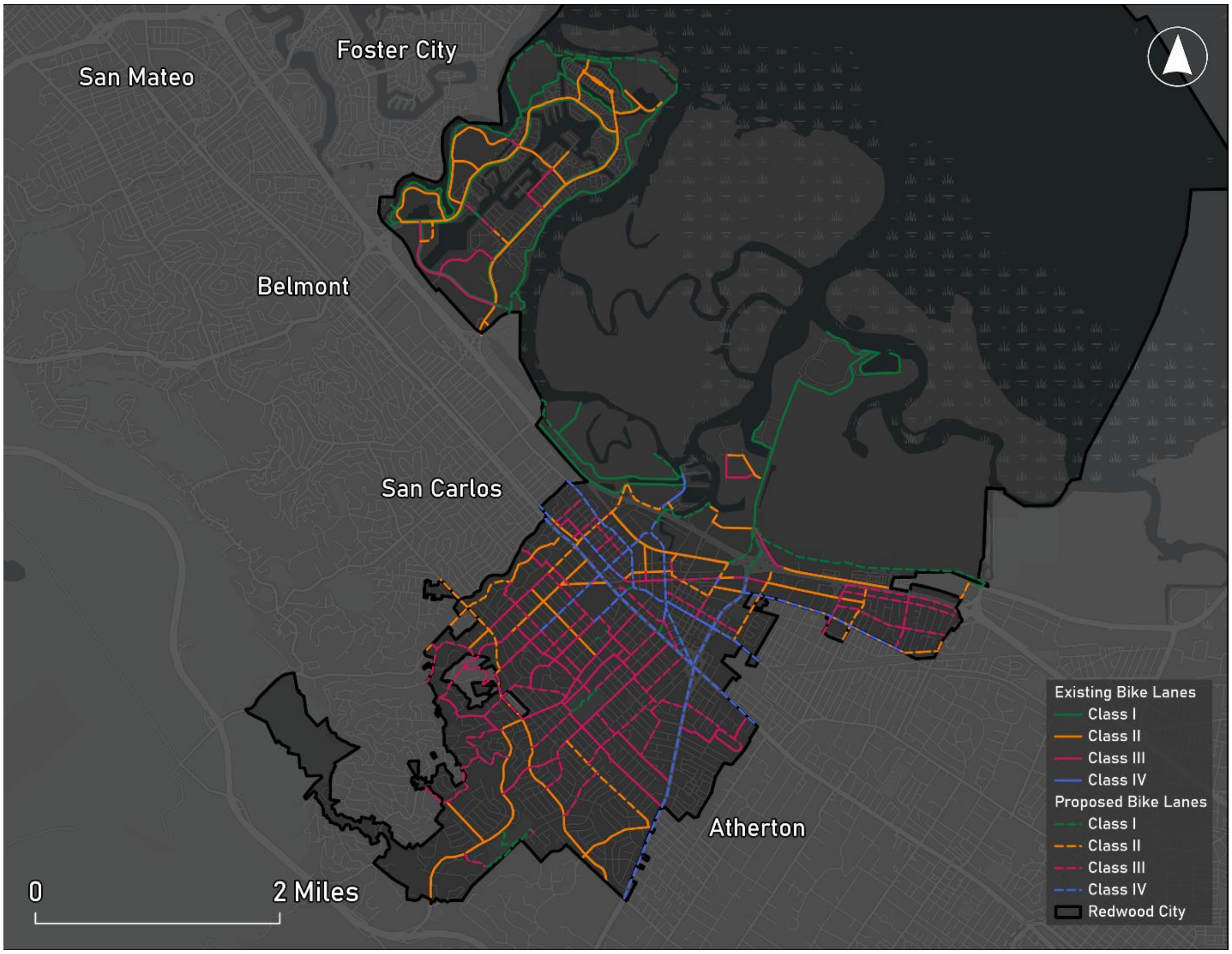


Figure 7. Existing and proposed bike lane network

1.4 Motivation

As a primary mode of urban transportation, cycling shows immense promise as it is faster than walking and better for the environment than driving. A cyclist is also 10 times less likely to seriously injure or kill pedestrians when compared to an automobile driver (Wardlaw 2000). Both of these facts make cycling a good option for local transit, especially for travel distances under five miles (Qin et al. 2018). The US lags behind many countries in prioritizing safe cycling; with its significant automotive culture, it has historically been rare for policymakers to propose investing in cycling infrastructure instead of car-centric infrastructure. By ignoring cycling, municipalities are depriving their citizens of the benefits of biking as a form of transportation, such as lower rates of obesity and heart disease (de Hartog et al. 2010), fewer greenhouse gas emissions (Dave 2010), less noise pollution (Pucher and Buehler 2008), as well as the opportunity for improved mental health that biking provides (Olsson et al. 2013). Instead, Americans are left to be content with driving most places and sitting in traffic for hours, just to get to work.

Spatial science and GIS, especially in the context of geodesign, are becoming increasingly recognized as powerful tools for urban planning. GIS has tremendous value when making urban planning decisions and can effectively guide city layout and design practices (Weimin and Milburn 2016). This project developed a methodology in which GIS plays a heavy role. GIS was first used to quantify the bikeability of the study area. Additional GIS techniques were then deployed to determine the impact of proposed bike lanes on issues related to equity in terms of local access to efficient and safe transportation options. Similar studies have been conducted in the past, albeit for different study areas, and their methodologies serve as inspiration for the design of this thesis' bikeability evaluation overlay. These studies have taken place around the world such as in Nigde, Turkey (Olgun 2020), Barranquilla, Colombia (Arellana et al. 2020), Vancouver, Canada (Winters et al. 2013), and Portland, United States (McNeil 2011). This project was conducted on the Bay Area Peninsula, which resulted in a unique output given the study area's topography, demographics, and progressive ideology which includes a strong promotion of bicycle transit and transit-oriented development. The output metrics were then made accessible to policymakers who can use the information to guide decisions regarding where to improve bicycle infrastructure, and how to best do it.

The author also has personal interest in this topic. As a Redwood City native, the author has witnessed firsthand the lack of bikeable infrastructure in the city and has significant interest in helping to improve it by providing policymakers with evidence to make their decisions. In addition, as a dual-citizen of the United States and the Netherlands, the author has witnessed firsthand how effective bike infrastructure in the Netherlands contributes to biking being a feasible method of transportation for all. As a result, the author has a desire to draw upon some of the urban design techniques found in the Netherlands as inspiration for cycling infrastructure in Redwood City, doing so through the application of a geodesign methodology.

The ultimate goal of this work was to produce deliverables that both underline the importance of bikeability in the United States and exemplify a methodology for evaluating and designing bike infrastructure. The contents of this thesis will hopefully lead to more cities adopting a pro-bicycle stance in terms of local transportation. It also highlights and encourages the application of the field of geodesign, a discipline that shows immense value and promise as an urban design tool.

1.5 Thesis Overview

The remainder of this thesis includes four chapters. The related literature chapter covers topics including the health and environmental benefits of cycling, the relationship between social factors and demographics and cycling, the utility of GIS in evaluating bikeability, and urban design techniques that can be applied to improve bikeability. The methods chapter outlines the techniques that were used to conduct the thesis and provides justifications for certain decisions made during the process. The results chapter describes the outputs of the methodology while the conclusions chapter provides commentary on the results and future implications of the research.

Chapter 2 Related Literature

This chapter reviews literature on urban cycling and bikeability. To form a basis on which the goal of advancing cycling infrastructure is justified, resources that describe the benefits of biking and literature that discusses the social and physical factors related to cycling, are reviewed. To aid in the formulation of a methodology to quantify the bikeability of each street segment in Redwood City, literature that employs geospatial methodologies to evaluate bikeability are reviewed. Finally, studies on the relationship between urban design and bikeability are reviewed. These reviewed literatures formed the groundwork for the methodology devised and deliverables created for this project.

2.1 Benefits of Biking

Unlike alternative methods of transportation such as cars, motorcycles, and trains, biking does not require an external fuel source; rather the human body provides the kinetic energy required for movement. Biking is faster and more efficient than other human-powered forms of transportation such as walking and running, as it allows humans to travel further distances in shorter amounts of time.

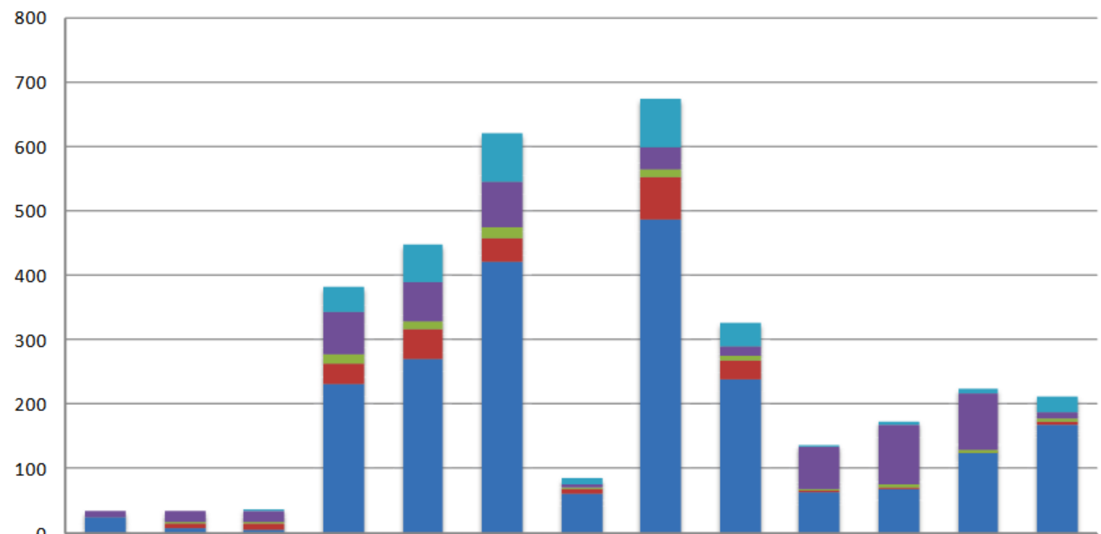
Because biking requires active movement by the rider, it is inherently beneficial to one's physical health. Cycling is a form of cardiovascular, aerobic exercise and can help riders maintain a healthy weight as well as lower their risk of heart disease (de Hartog et al. 2010). Regular cycling has also been associated with a lower cancer mortality and morbidity rate (Oja et al., 2011). Furthermore, the health benefits of biking far outweigh the risks posed by the dangers of engaging in cycling, such as the risk of accidents and exhaust inhalation (Götschi, Garrard, and Giles-Corti 2014). The risks of cycling are even lower if fewer cars are on the roads and cyclists are allotted bike pathways separate from the street (Monsere et al. 2014).

Regular cycling can improve mental health and boost one's mood. Olsson et al. (2013) surveyed 713 Swedish citizens on work commute, happiness, and demographics. The results of the survey suggest the level of satisfaction with one's work commute has a significant impact on that individual's well-being and that walking or biking are much more satisfying than driving or taking public transportation. However, in the US the disparity between satisfaction from driving versus biking to work is not as large as in Sweden (Olsson et al. 2013). This may be due to automotive commutes being more common in the US. Still, this study overall suggests that commuting via bike improves one's mood more than driving.

Ma, Ye, and Wang (2020) conducted a broad literature review and determined that additional studies have corroborated the conclusion that cycling, especially when used as a form of transportation rather than for leisure, can improve mental health by reducing feelings of anxiety and depression (Ma, Ye, and Wang 2021). In another study, Dill and Rose (2021), interviewed 28 individuals in Portland, Oregon who had recently switched from driving to using an electric bike to get to work. One individual claimed that by cycling, he was "able to turn the worst part of the day, which is getting in the car and driving to work into the best part of the day," implying that he finds his bicycle commute to be enjoyable (Dill and Rose 2021). Bicycles also produce practically zero noise pollution, making them a peaceful transit option (Pucher and Buehler 2008). Less exposure to traffic noise may provide other health benefits, as a 2018 study found that exposing mice to traffic noise increased stress and anxiety and led to quicker brain impairment and cognitive decline in the rodents (Jafari, Kolb, and Mohajerani 2018).

In addition to providing physical and mental health benefits, cycling is a form of environmentally conscious transportation that emits significantly less greenhouse gasses and noise pollution than alternative forms of travel. The primary environmental benefit of cycling is that bicycles do not require the use of environmentally detrimental fossil fuels, and instead rely on renewable resources taken in by the rider (Pucher and Buehler 2008). A study in Shanghai investigated the environmental impacts of a bike-sharing system in which users rent bikes, likely reducing automotive reliance. The study determined that in 2016, the program saved 8,358 tons of gasoline. It also determined that carbon dioxide emissions had been reduced by 25,240 tons and nitrogen dioxide by 64 tons (Zhang and Mi 2018). In the United States, a predictive study performed in Portland, Oregon estimated that if 15% of passenger miles traveled were completed on e-bike, carbon dioxide emissions could decrease by 12% (McQueen, MacArthur, and Cherry 2020). This provides evidence that an increase in cycling can quell climate change.

The bicycle manufacturing process is still inherently bad for the environment, given the need for extracted mineral resources and the emissions released by factories and during the transportation of parts (Chan, Schau, and Finkbeiner 2019). Regardless, the amount of greenhouse gasses emitted over a bicycles' lifespan is significantly lower than that of cars. This is largely due to the disparity in associated emissions when being used as a means of transport. A 2010 study was undertaken to compare the difference in greenhouse gas emissions between different modes of transportation. The study investigated the emissions related to the fuel production, infrastructure, maintenance, manufacturing, and operation of 13 different transportation options. The amounts of emissions per each form of transportation can be seen in Figure 8, which comes directly from the study (Dave, 2010). It was determined that the average SUV emits 446 kilograms of greenhouse gasses per passenger-mile-traveled while bikes emit 33 kilograms of greenhouse gasses per passenger-mile-traveled (Dave 2010). Lastly, bikes require much less space than cars, suggesting that an increase in bike ridership could lead to a decrease in construction of large roads and parking garages which would eliminate the large amounts of embodied carbon associated with those types of infrastructure (Pucher and Buehler 2008).



	Walking	Bicycling	Ebike	Sedan	SUV	Pickup	Bus on Peak	Bus off Peak	Bus Average	BART	MUNI	Green Line	Boeing 737
Total	33	33	33	382	446	619	85	674	326	136	173	224	210
Fuel Production	0	0	0.33	39	58	74	10	77	36	3	4	8	23
Infrastructure	9	17	17	65	59	71	4	34	16	64	94	87	11
Maintenance	0	1	1	15	14	17	1	12	6	2	4	4	4
Manufacturing	0	8	11	34	45	38	8	66	31	2	2	1	4
Operation	24	7	4	230	270	420	61	486	237	64	69	123	168

Figure 8. Emissions of 13 modes of transportation in kg GGE/PMT (Dave 2010)

2.2 Social Factors and Bikeability

Social factors influence the convenience and safety of biking and a number of studies have been conducted to identify specific relationships. Lindsey performed spatial analysis to estimate the likelihood of a crash at all intersections and mid-blocks in Minneapolis based on historic crash data (Lindsey et al. 2019). The output was then compared with demographic data and revealed that a higher crash risk was related to areas with a lower average income, a majority-minority population, and proximity to primary arterial roads.

These findings have been observed in other American cities, such as Los Angeles where the risk of a crash involving a pedestrian was higher in areas with high Hispanic populations (Loukaitou-Sideris 2007). The study first identified a correlation between high poverty rates and high Hispanic populations, aggregated by census tract. It then concluded that because of lower economic status, a greater percentage of the Hispanic community, and other minority communities, are more likely to walk, bike, and take public transportation. These forms of transportation put them more at risk of being a pedestrian victim in a vehicular accident. A 2019 study corroborated these findings using a regression analysis that compared the distribution of cycling infrastructure and various demographic statistics. The study determined that worse access to bike lanes was most often seen in communities with low educational attainment, high rates of Hispanic residents, and a lower composite socioeconomic status (Braun, Rodriguez, and Gordon-Larsen 2019).

Unequal access to cycling infrastructure between different social groups is not a coincidence, as there is evidence that issues related to equity have often been overlooked when planning and implementing cycling infrastructure (Cunha and Silva 2022). Cunha and Silva present a literature review on studies that discuss the distribution of cycling infrastructure within communities. They determined that overall, cycling infrastructure has often been implemented more in wealthier and privileged communities than historically underserved communities. This suggests that change is needed in municipal cycling infrastructure planning processes. It is critical that the equity impacts of projects are considered.

Age is another important demographic statistic that has a relationship with bikeability, as some age groups may be in more need of safe infrastructure than others. Communities with a higher population of children have been observed to have higher crash risk (Cottrill and Thakuriah 2010), which has significant implications for neighborhoods with many children walking or biking to school. A qualitative study that interviewed 186 parents in Texas gained insight into the barriers to cycling that children face. It determined that the existence of quality sidewalks and crosswalks as well as other built-environmental factors played the largest role in determining whether or not children would walk or bike or drive to school (Kweon et al. 2006). In communities with a high youth population, extra care must be taken when implementing cycling infrastructure, as it must be able to protect inexperienced and vulnerable riders. Additionally, if schools spearhead activities related to teaching bike safety or organizing bike-to-school days, it is likely that ridership will increase (Staunton and Hubsmith 2003). However, these policies must be implemented in conjunction with infrastructure improvements.

This thesis incorporates crash data as areas with a high volume of crashes are less bikeable than areas with fewer crashes (Codina et al. 2022). Following the evaluation of bikeability using contributing input variables, the results are analyzed with a social lens allowing for relationships between bikeability and various social demographics to be identified. By acknowledging the disproportionate amount of pedestrian and vehicular accidents in areas with a larger youth population, lower median income, and/or higher non-white percentage, city planners can strive to improve access to safe bike lanes when designing future infrastructure improvements.

2.3 GIS Methodologies and Bikeability

GIS is a powerful tool that can be applied to perform analyses involving spatial data. In terms of studies related to bikeability and the methodologies used in this thesis, GIS was used to quantify the bikeability of Redwood City and evaluate the equity impact of proposed cycling infrastructure projects.

2.3.1 Variables Used to Quantify Bikeability

GIS overlay methodologies have been used to gauge the bikeability of a study area (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Grisé and El-Geneidy 2018; Krenn, Oja, and Titze 2015; Olgun 2020; Porter et al. 2020; Winters et al. 2013). Bikeability quantification using an overlay methodology is a method of geospatial analysis used in this thesis. Previous studies that have used similar methodologies each used their own unique set of input variables that are combined in a weighted sum to quantify bikeability. While each set is different, there are commonalities between studies in terms of variables used (Table 1).

Table 1. Variables used in previous bikeability studies

Variable	Studies
Bike lanes	Arellana et al. (2020); Codina et al. (2022); Grigore et al. (2019); Krenn, Oja, and Titze (2015); Porter et al. (2020); Winters et al. (2013)
Building aesthetics	Arellana et al. (2020)
Connectivity	Codina et al. (2022); Grisé and El-Geneidy (2018); Winters et al. (2013)
Crime rate	Arellana et al. (2020)
Destinations	Porter et al. (2020); Olgun (2020); Winters et al. (2013)
Estimated cycling trips	Grisé and El-Geneidy (2018)
Existing cycling trips	Grisé and El-Geneidy (2018)
Hazards	Arellana et al. (2020); Codina et al. (2022); Grigore et al. (2019); Grisé and El-Geneidy (2018)
Lighting	Arellana et al. (2020)
Ozone level	Porter et al. (2020)
Population density	Porter et al. (2020)
Police presence	Arellana et al. (2020)
Security camera presence	Arellana et al. (2020)
Road quality	Arellana et al. (2020)
Slope	Arellana et al. (2020); Codina et al. (2022); Grigore et al. (2019); Krenn, Oja, and Titze (2015); Olgun (2020); Winters et al. (2013)
Speed limit	Arellana et al. (2020); Grigore et al. (2019)
Traffic	Arellana et al. (2020); Codina et al. (2022); Grigore et al. (2019); Olgun (2020)
Tree canopy	Arellana et al. (2020); Grigore et al. (2019); Krenn, Oja, and Titze (2015); Olgun (2020); Porter et al. (2020)

Among the variables most commonly used in the eight investigated studies are bike lanes, destinations, hazards, slope, speed limit, and tree canopy. These variables and their utility to bikeability studies are described in sections 2.3.1.1 through 2.3.1.6.

2.3.1.1 Bike lanes

In bikeability studies, bike lanes as a variable refers to the presence of designated bike infrastructure within a study area. The existence of official bike lanes alone elevates an area's bikeability, as it allots cyclists their own space to ride. However, the quality and effectiveness of the bike lane can vary depending on the type of lane or pavement condition.

Quantifying bike lanes for use in an overlay methodology has been performed in previous studies. Arellana et al. (2020) applied a polyline overlay methodology where each road segment was assigned a bikeability score. Each road segment received a bike lanes attribute that functioned in a binary manner. If a given road had a designated bike lane, it received a score of one, but if it did not have a designated bike lane, it received a score of 0 (Arellana et al. 2020). Winters et al. (2013) differed in that a raster weighted overlay was conducted to perform a bikeability analysis. The presence of bike lanes was still used as an input factor, but in the form of a bicycle route density raster layer. To create this raster, a feature layer of existing designated bike lanes was analyzed using the *Line Density* tool in ArcGIS. The result was a raster representing the presence of bike lanes that could be integrated into a weighted overlay (Winters et al. 2013). The use of the *Line Density* tool also allowed for a non-binary approach, meaning that raster cells that may not contain their own bike lanes, but are adjacent to bike lanes, receive a boost in conductivity to bikeability. This is more realistic, as residents would most likely be willing to travel a few blocks on unprotected paths to reach bikeable infrastructure.

2.3.1.2 Destinations

Destinations is a generalized variable that differs slightly between each study. It relates to the zoning and land use of a study area, as some zones and uses are more conducive to bikeability and would induce more residents to cycle. Types of destinations that fit these characteristics include parks and transit stations (Porter et al. 2020) as well as commercial, education, entertainment, and office facilities (Winters et al. 2013). Winters et al. (2013) quantified the location and distribution of destinations by selecting parcels that fit the aforementioned destination types from a broader land use dataset in a GIS. A new layer was created from the selection featuring only parcel polygons that represented destination locations and was converted into a point file. The point file was then input into the ArcGIS *Point Density* tool to produce a raster showing the density of destination locations across the Vancouver Metropolitan Area (Winters et al. 2013). This raster was then used in the final bikeability weighted overlay evaluation.

2.3.1.3 Hazards

Hazards is another generalized variable that may refer to a variety of factors that influence bikeability. Broadly, hazards refer to potential dangers that a cyclist may encounter while riding their bike. One example of a hazard is the existence of physical bike lane obstructions including poles (Arellana et al. 2020) and tram tracks and crossings (Grigore et al. 2019). Hazards may also refer to dangerous intersections along bike routes (Grisé and El-Geneidy 2018) and the number of cyclist-involved collisions along a given road (Codina et al. 2022). Codina et al. (2022) used hazards as one of their five input variables for their bikeability evaluation in Barcelona. This was done by dividing the study area into a grid of 100 meter (m) by 100m cells and then calculating the rate of collisions per bike ride for each cell. This process resulted in a raster layer that could be used as an input layer into the weighted overlay analysis (Codina et al. 2022).

2.3.1.4 Slope

Slope has a significant impact on bikeability. If the steepness of a street is over 10 degrees, it is extremely difficult to cycle uphill and would deter most average bikers (Arellana et al. 2020). Slope is a common variable in bikeability evaluations. Krenn et al. (2015) used slope as one of five input factors in their bikeability evaluation of Graz, Austria. To evaluate the bikeability in Graz, a weighted overlay of five input rasters was conducted. Each raster was 100m by 100m. In the slope raster, each cell held a value that represented the mean slope of that cell. These values were later reclassified to fit within a common one to seven scale that could be used to compare all five rasters together (Krenn et al. 2015). Winters et al. (2013) also incorporated slope as one of five input variables in their bikeability evaluation of the Vancouver Metropolitan Area. To quantify slope, a 30m-by-30m digital elevation model (DEM) was acquired and used as the input for the *Slope* geoprocessing tool in ArcGIS. The output was set to percentage rise which assigned each 30m-by-30m cell value of the maximum slope between itself and bordering cells. This resulting raster was then used as one of five rasters in the bikeability weighted overlay (Winters et al. 2013).

2.3.1.5 Speed limit

Street speed limits have a significant impact on the amount of safety and attractiveness that roads offer cyclists. Fast speeds are less safe for cyclists. In fact, cycling guidelines in Switzerland, the Netherlands, and Denmark state that cyclists should not share space with cars when the speed limit exceeds 30 to 40 kilometers per hour, which is approximately 20 to 25 miles per hour (MPH) (Grigore et al. 2019). Grigore et al. (2019) and Arellana et al. (2020) both used speed limit as an input factor in their bikeability overlays. Rather than perform a weighted overlay using raster data, both studies performed overlay analysis on street segments, with segment speed limit acting as one input variable. Grigore et al. (2019) acquired speed limit spatial data for the study area, Basel, Switzerland, from the Office of Mobility Basel-Stadt while Arellana et al. (2020) acquired data that represented the motorized transport speed of each road segment in the study area, Barranquilla, Colombia, from the 2012 Master Mobility Plan for Barranquilla.

2.3.1.6 Tree canopy

A strong tree canopy or high percentage of tree coverage can increase the level of bikeability by improving the aesthetics of the bike ride (Arellana et al. 2020) and cooling down urban areas during warm periods of the year (Hinterthuer 2019). Arellana et al. (2020) quantified trees by evaluating each road segment in the study area for the presence of trees. The scoring system was binary and if a segment had trees, it received a score of one, and if a segment did not have trees, it received a score of zero (Arellana et al. 2020). Krenn et al. (2015) incorporated green cover, which includes trees, shrubs, and grasses, into their raster overlay evaluation of bikeability. For each 100m-by-100m cell within the study area, the total area of green coverage was calculated. Ultimately, each cell contained a value that quantified its total green coverage and this raster was used as one of five inputs into the bikeability evaluation overlay (Krenn et al. 2015).

2.3.2 GIS Methodologies to Quantify Bikeability

Using GIS to evaluate the bikeability of a study area is not a novel application of spatial sciences and multiple studies have been successful at doing so in the past.

A 2020 geospatial research study conducted in Portland, Oregon aimed to quantify bikeability based on the location of desirable destinations (retail, schools, parks, transit stations, etc.) and surveyed individual's biking habits as the primary input information (McNeil 2011). The study determined that the average Portland cyclist is willing to travel up to 2.5 miles by bike (roughly 20 minutes) but is willing to travel 22% further along a protected bike lane, which is physically separated from car lanes, as opposed to a bike lane, which provides no physical separation from passing cars. This study geocoded a number of locations people would bike to on a regular basis such as stores, parks, schools, and other amenities. Each amenity type was assigned a score, with the total sum of scores across all amenity types being 100. Thirteen arbitrary locations in varying neighborhoods and of varying distance from existing bike infrastructure were then selected as 'origin points' and a raster illustrating each point's service area, with breaks at 1 mile, 2 miles, and 2.5 miles, was created (see Figure 9).

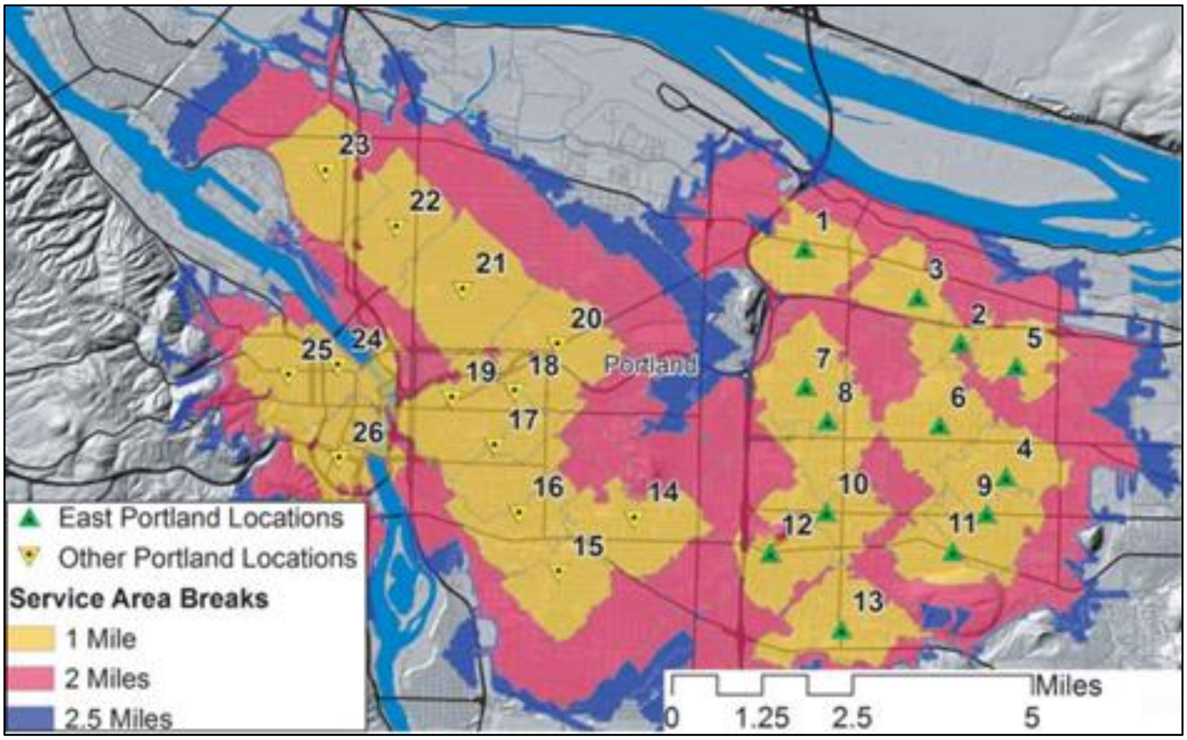


Figure 9. Portland service area breaks

Next, the bikeability score for each origin point was created by calculating the sum of all amenity scores in the area, where point deductions were imposed for amenities further from the origin point. This allowed the researchers to create a map which shows bikeability score at each origin point, allowing them to deduce trends in bikeability across the city (Figure 10).

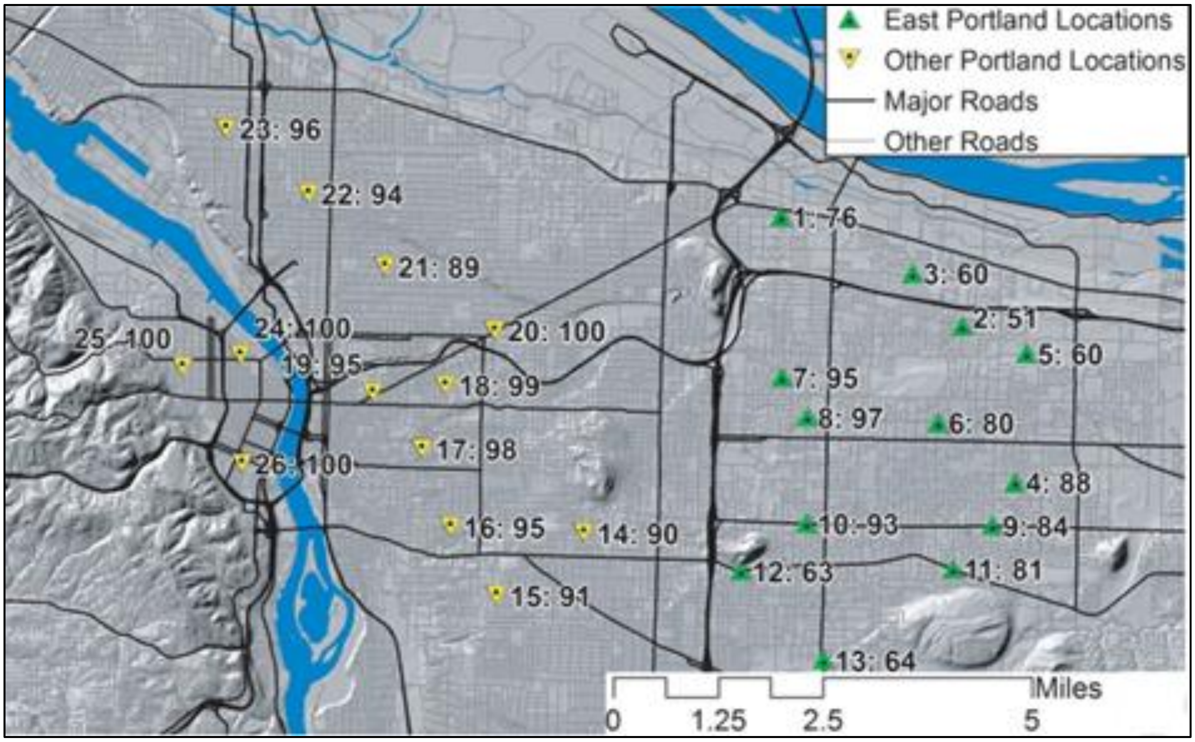


Figure 10. Portland bikeability scores

Bikeability scores for Portland, OR show a range from 51 (break area 2) to 100 (break areas 20, 24, 25, and 26) and overall suggest bikeability is higher in the western half of the city compared to the eastern half of the city. In addition, the study also determined that a lack of road connectivity, which refers to the density of intersections and ease of moving around a street network, was the biggest factor weighing down areas with poor bikeability (McNeil 2011). While it provided valuable insight regarding bikeability, the Portland study did not use a weighted overlay, which is another useful strategy to assess the overall bikeability of an entire study area.

In contrast to McNeil's Portland study, a research study performed across the Vancouver, Canada Metropolitan Area used a weighted overlay to evaluate bikeability (Winters et al. 2013). For this study, five input rasters were used: topography, destination density, street connectivity, bike route separation, and bike route density (see Figure 11). The Vancouver project created a raster output where each pixel holds a value that defines the level of bikeability. The result is a continuous map that quantifies bikeability in the Vancouver area (Figure 11). Winters' methodology was precedent for a similar study in Graz, Austria that used a weighted overlay with cycling infrastructure, presence of separated bicycle pathways, main roads without parallel bicycle lanes, green and aquatic areas, topography, and land-use as input factors (Krenn, Oja, and Titze 2015). The study successfully quantified bikeability within the study area. These types of overlay methodologies and symbology techniques serve as inspirations for the methodology devised in this thesis.

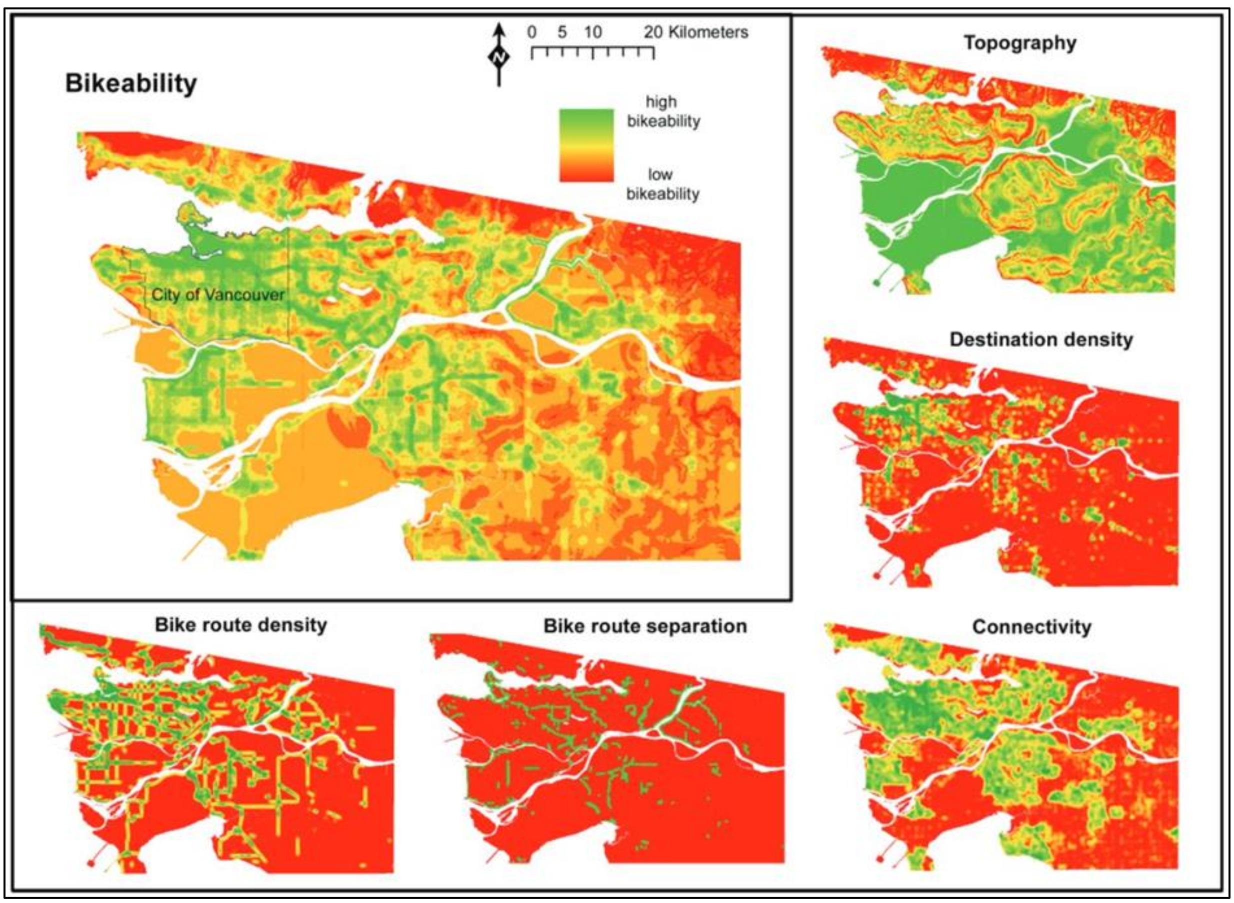


Figure 11. Input factors and bikeability for the Vancouver Metropolitan Area

A third study that implemented a weighted overlay to assess bikeability was undertaken in Barranquilla, Colombia. This study was unique due to the use of community engagement to determine which bike infrastructure projects should be prioritized (Arellana et al. 2020). The project began by designing an overlay methodology to create a bikeability index. Local bikers were interviewed to provide insights into popular biking origins and destinations, and this information was overlaid with the bikeability index to determine project priority.

2.3.3 Evaluating the Equity Impact of Cycling Infrastructure

Overlay methodologies can also be used to gauge the extent to which proposed bike lanes may mitigate issues related to inequity as discussed in section 2.2. By overlaying polygons that represent certain equity elements, such as income, ethnicity, or state-identified equity zones, it is possible to deduce which parts of the study area are faced with the most challenges related to inequality. However, prior to beginning the analytical process, it is important to have background knowledge regarding previous studies performed in a similar vein, and these are reviewed here.

In addition to assessing bikeability, this thesis analyzed a set of existing proposed bicycle infrastructure projects in Redwood City and determined which ones should be prioritized in terms of implementation by the city. While the exact methodology used in this thesis is novel, previous studies have performed similar analyses for similar reasons. In 2018, an analysis was carried out in Auburn, Alabama to determine where new bike share stations should be located as well as in what order their installation should be prioritized. The researchers began by using a weighted overlay methodology to determine which parts of the city would have the highest demand for bike share facilities. They then overlaid the resulting map with a map of existing bike share facilities. Next, they used visual observation, demographic statistics, and an activity-transit accessibility index to determine the impact and utility of the proposed locations to ultimately decide which sites to prioritize (Jehn, Atiquzzaman, and LaMondia 2018).

Grisé and El-Geneidy (2018) aimed to develop a prioritization ranking for new bike lanes in Quebec City, Canada. A weighted overlay was generated with input factors that included existing and expected trips based on survey results, the locations of suggested bike lanes, dangerous intersections, and network connectivity. This resulted in the identification of locations where bike lanes should be prioritized. The authors continued their research by considering equity and historic social inequality within the study area. An index was created to identify communities based on median household income, unemployment, immigration, and relative housing cost. These areas roughly overlapped with areas that should be prioritized based on the weighted overlay results (Grisé and El-Geneidy 2018).

2.4 Urban Design Techniques for Improved Bikeability

There are a variety of effective methods that can be applied to improve the bikeability of a study area. These methods include public engagement, municipal policy, physical infrastructure, and the use of geodesign as a guiding methodology.

2.4.1 Public Engagement

A city can boost its urban design process using policy tools and infrastructure upgrades, and improvements can be maximized by allowing residents and other local stakeholders to have input during the design process. Engaging citizens through polls, workshops, and meetings allows decision makers to provide designs that best serve their constituents.

When hosting a workshop with members of the public, it is important to feature interactive components where participants can easily contribute feedback (Mueller et al. 2018). This is especially true in design and spatial sciences, where interactive maps and renderings maximize public participation and best engage stakeholders. However, it is critical that the interactive component is designed in a simple and accessible way, to avoid overcomplicating the task of public stakeholders and turning them away from contributing feedback (Mahyar et al. 2016). Prior to hosting a public engagement session, it is necessary to be aware of common pitfalls found when working with stakeholders to best mitigate them. For example, public engagement workshops have the potential to become argumentative, or foster unfair situations in which one individual or interest group dominates the conversation (Duan 2021). By implementing group work, limiting the amount of time people can speak, and using engaging techniques to boost interest, certain drawbacks can be avoided (Duan 2021).

2.4.2 Policy Tools

Policy tools to improve bikeability can be written based on the results of research and observation. If crafted well, municipal policy can increase the number of cyclists within a region.

In Copenhagen, Denmark, municipal goals have been set to reduce carbon emissions and improve general well-being. For example, the city aims to have 50% of work and school commutes be completed via cycling. Policymakers have developed several tools to assess progress and move towards completing these goals. The techniques include bi-annual indicators and metrics and stakeholder and public engagement (Nielsen, Skov-Petersen, and Carstensen. 2013).

Hull and O’Holleran (2014) describe a methodology involving literature and case study reviews on instances where cities have successfully created cycling-conducive infrastructure. As a guiding principle, the research claimed that it is imperative that governments consider bicycles as, at minimum, equal agents when compared to cars. Cities can then adjust their urban plans and policy to form neighborhoods with a diverse mixture of land use where resources are readily available within a small distance to all modes of transportation. Lastly, the research indicates that dissuading car use through car taxes and use restrictions can effectively encourage cycling (Hull and O'Holleran 2014).

2.4.3 Physical Infrastructure

Urban connectivity refers to the extent to which a city is easily navigable and traversable and is dependent on the street layout and available transit options. Galpern et al. (2018) monitored cell phone GPS data over a six-year period to assess the mobility of college students in Calgary, Canada. The researchers determined that students living in neighborhoods with low street connectivity were more inactive and car-reliant than students living in neighborhoods with high street connectivity and who were more mobile and reliant on walking and biking. This suggests that good street connectivity increases the walkability and bikeability of a city (Galpern et al. 2018). In general, creating urban environments with high population density, a good mixture of land use, and good walking and biking infrastructure (including high connectivity) are additional physical infrastructure characteristics that boost bikeability and minimize car dependence (Saelens, Sallis, and Frank 2003).

Existing literature also outlines the types of cycling infrastructure that are most effective. While the addition of any cycling infrastructure increases ridership (Parker et al. 2013), the lane design is still critical to maximize the amount of people who are comfortable using the new infrastructure. In nearly any context, fully protected bike lanes are the optimal type of infrastructure. Cycle tracks, and bike boulevards on slow streets, are the only types of bike infrastructure that demonstrate a notable decrease in crash risk (DiGioia 2017) and reduce injury risk (Thomas and DeRobertis 2013). However, it is not enough to construct a standalone, fully protected bike lane. A 2021 study in Sydney, Australia used a predictive transport mode choice model to estimate the number of cyclists in two design scenarios. The first scenario involved the implementation of a singular cycleway while the second scenario involved the implementation of an entire network. The model predicted that while the first scenario will increase cycling, it mainly catered to male, high-income, and older social groups. However, the second scenario catered to a wider variety of social groups (Standen et al. 2021). This implies that while a city must start by implementing an initial protected bike lane, they must continue towards a complete network. The construction of a complete and bikeable network would induce demand, increasing the number of cyclists. Fosgerau et al. (2023) investigated the relationship between bicycle infrastructure and induced demand in Copenhagen using a series of spatial simulations. They determined that the existence of a complete network increases the number of bicycle trips by 59% and the total distance cycled by residents by 88% (Fosgerau et al. 2023).

2.4.4 Geodesign as a Tool to Improve the Built Environment

While urban design has tremendous influence over improving bikeability, geodesign shows great potential for making cities more livable at the human level by using a mixed-methods and holistic approach. Geodesign combines geospatial analysis with architectural and urban design fundamentals as well as community engagement to make decisions regarding infrastructure and planning, making it a complex, interdisciplinary field (Campagna 2016). Geodesign manages to combine analytical tools with human creativity (Li and Milburn 2016), resulting in the creation of enjoyable and useful environments.

Chapter 3 Methods

This thesis utilizes an interdisciplinary and mixed methods geodesign approach. Applying a geodesign methodology allows for the consideration of a multitude of interdisciplinary fields when making decisions and emphasizes the importance of sustainable design. This thesis makes use of technical skills found in the fields of GIS, architecture, and urban design and combines them with soft skills such as public engagement and iterative and sustainable design to advance bikeability in Redwood City.

3.1 Methods Overview

The methodology applied for this thesis is split into five distinct steps. The first three steps were all completed individually, before being assessed together in step four which fed into step five.

First, the existing state of bikeability for each road segment in Redwood City was assessed in ArcGIS Pro by using a linear weighted sum overlay of spatial data relevant to bikeability.

Second, a workshop involving Redwood City residents was held to solicit input on the existing state of cycling within Redwood City as well as residents' wishes for future infrastructure improvements. The workshop findings were quantified and added to ArcGIS Pro for further spatial analysis.

Third, an analysis on the extent to which each proposed project impacted historically underserved communities was performed in ArcGIS Pro using four datasets that described the spatial extent of local underserved communities. Each proposed project was assigned an equity score based on their spatial relationship with the four aforementioned datasets.

Fourth, a weighted sum methodology was used in ArcGIS Pro to give each proposed project a prioritization score. This determined the order that the implementation of proposed projects should be. The highest scoring projects were located in areas with low bikeability, underserved populations, and areas that received specific mentions by residents during the workshop.

Fifth and lastly, design concepts and renderings were created in SketchUp for the three highest priority projects. An overview of the project methodology can be seen in Figure 12.

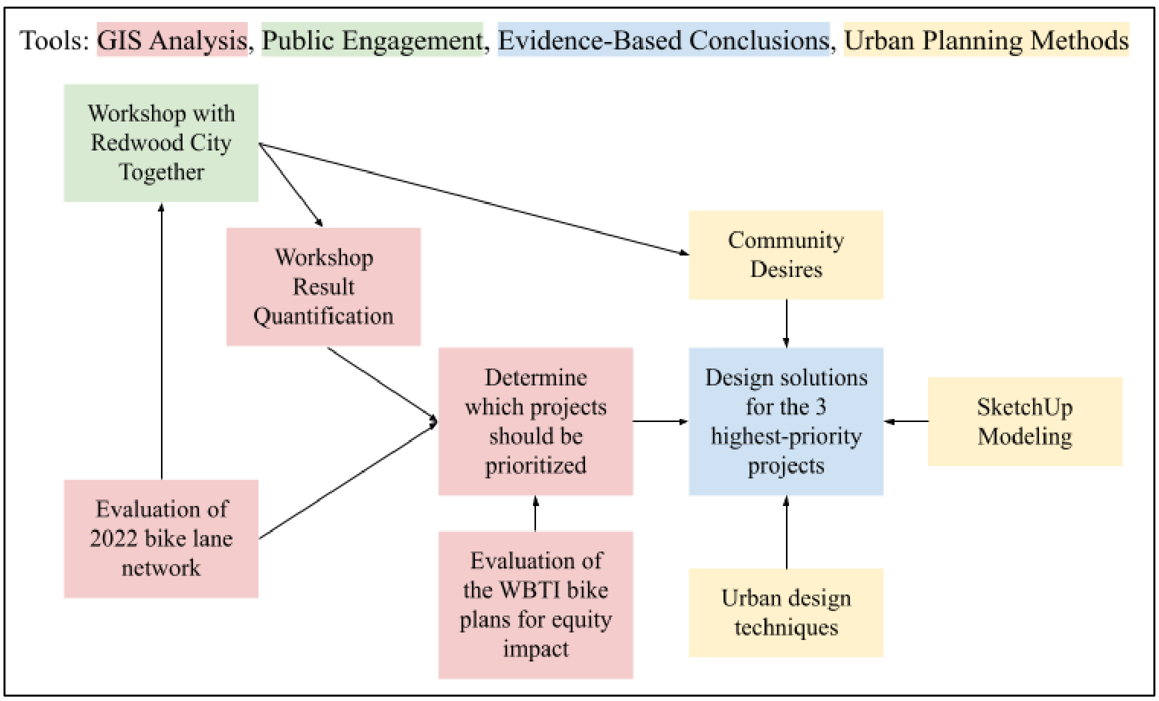


Figure 12. Methodology overview

3.2 Bikeability Quantification

Developing a bikeability score for each road segment within Redwood City involved spatial analysis in ArcGIS Pro using six input variables that impact bikeability. The data representing each variable were project into the 1983 NAD California Zone III State Plane coordinate system, which ensures a high level of geographic accuracy for data in Redwood City.

The data were then reclassified to a common scale and combined using a weighted sum to produce a final bikeability score for each street segment. The weights for each input variable were selected based on weights used for identical variables in similar studies.

3.2.1 Variable Choices and Data Preparation

The six variables used in this study were selected based on data availability as well as the frequency in which they were used in previous literature. Of the eight investigated bikeability studies, speed limit was used two times (Arellana et al. 2020; Grigore et al. 2019), destinations (zoning designation in this thesis) was used three times (Olgun 2020; Porter et al. 2020; Winters et al. 2013), slope was used six times (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Krenn, Oja, and Titze 2015; Olgun 2020; Winters et al. 2013), tree canopy was used five times (Arellana et al. 2020; Grigore et al. 2019; Krenn, Oja, and Titze 2015; Olgun 2020; Porter et al. 2020), the presence of bike lanes (existing bike lane access in this thesis) was used six times (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Krenn, Oja, and Titze 2015; Porter et al. 2020; Winters et al. 2013), and hazards (crashes in this thesis) was used three times (Arellana et al. 2020; Grigore et al. 2019; Grisé and El-Geneidy 2018). No other input variable found in the eight studies was used more than once. These six datasets were acquired and prepared for use in this thesis and can be seen in Table 2 along with other data that was used in this project.

Table 2. Required data

Data Layer	Utility	Source	Format	Date Last Updated
CA Healthy Places Index	Equity analysis	California Healthy Places Index	Polygon	2022
C/CAG Equity Focus Areas	Equity analysis	C/CAG Github	Polygon	Unknown
Census Tracts	Create equity polygon data	US Census	Polygon (Shapefile)	2022
Crashes	Bikeability input variable	Transportation Injury Mapping System	Point	2022
DEM	Bike lane access variable	USGS	Raster (10m)	11 August 2022
Demographic Block Groups	Equity analysis	San Mateo County GIS Open Data	Polygon (Shapefile)	17 December 2015
Existing Bike Lanes	Bike lane access variable	RWC WBTI	Polyline (KML)	June 2022
MTC Equity Priority Areas	Equity analysis	MTC GIS Open Data	Polygon (Shapefile)	25 May 2021
Parks	Workshop quantification	San Mateo County GIS Open Data	Polygon (Shapefile)	5 June 2015
Proposed Bike Lanes	Indicate location of proposed bike lanes	RWC WBTI	Polyline (KML)	June 2022
Redwood City Boundary	Clip input boundary and feature on maps	California Open Data Portal	Polygon (Shapefile)	1 January 2016
Redwood City Neighborhoods	Cartography	*Vbeckley_RWC* on ArcGIS Online	Polygon (ArcGIS Online)	29 January 2018
SamTrans	Equity analysis	*ShockleyD_Samtrans* on ArcGIS Online	Polygon (ArcGIS Pro)	11 February 2022
Schools	Workshop quantification	San Mateo County GIS Open Data	Polygon (Shapefile)	5 June 2015
Speed Limit	Bikeability input variable	County of San Mateo GIS Data Download	Polyline (Shapefile)	2022
Tree Canopy	Bikeability input variable	Multi-Resolution Land Characteristics Consortium	Raster (30m)	2016
Zoning Designation	Bikeability input variable	Redwood City Community GIS	Polygon	Unknown

3.2.1.1 Speed limit

Speed limit was selected as an input variable for the bikeability evaluation. Traffic speed has a significant impact on bikeability, as higher speeds are more dangerous for cyclists and make for a less appealing bike ride. In addition, speed limit was an input factor in some of the reviewed bikeability studies (Arellana et al. 2020; Grigore et al. 2019).

A polyline dataset was downloaded to ArcGIS Pro from the San Mateo County Government GIS Data Download website (Information Services 2022) and projected. This dataset contained road segments for each road within San Mateo County. Each segment features a variety of attribute information including street type, street name, and speed limit. This dataset was clipped using the Redwood City boundary dataset, which was downloaded from the California Government GIS Data Portal (California Open Data Portal 2019). The resulting polyline feature layer featured every road segment in the study area, including each segment's speed limit. This dataset was later modified to include additional fields that account for the other five bikeability input variables and was therefore renamed *BikeabilityVariables*.

A new field titled *SL_Value* was then created to host the reclassified values for speed limit. To properly conduct a weighted sum of multiple variables, each variable had to maintain an identical scale. A scale of one to 10 was chosen where 10 indicates highest conduciveness to bikeability and a score of one indicates lowest conduciveness to bikeability. Each of the six layers was transformed from a raw value to a numeric value and finally to a scaled value, fit for use in a weighted sum. Speed limits were reclassified and scaled as per Table 3. The scaled value for each speed limit was chosen based on existing literature that discusses the relative safety and comfort of biking on roads with different speed limits. Grigore et al. (2019) stated that the maximum speed cyclists should be expected to bike with cars is around 20mph. After that, the level of protection offered to cyclists should sequentially increase at approximately 25mph, 40mph, and 45mph (Grigore et al. 2019). As such, speed limits below 20mph were scaled to the maximum value, 10, while faster speed limits quickly dropped off in scaled value.

Table 3. Speed limit reclassification

Raw Value	Reclassified Value	Scaled Value
0 MPH	0	10
10 MPH	10	10
15 MPH	15	10
25 MPH	25	8
30 MPH	30	6
35 MPH	35	6
45 MPH	45	3
65 MPH	65	1

To reclassify the values, the newly created *SL_Value* attribute was calculated using the following Arcade script:

$$\begin{gathered} var\ x\ =\ \$feature.SPEEDLIMIT \\ var\ nx\ =\ When(x\ ==\ 0, 10, \\ x\ ==\ 10, 10, \\ x\ ==\ 15, 9, \\ x\ ==\ 25, \\ 7, x\ ==\ 30, 5, x\ ==\ 35, 4, x\ ==\ 45, 3, x\ ==\ 65, 1, 'NONE') \\ return\ nx \end{gathered} \tag{1}$$

where *x* refers to the speed limit attribute of the road segment as set by *$feature.SPEEDLIMIT* and *nx* represents the new speed limit classification of the road feature, dependent on the value of *x*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and assigns values to the *SL_Value* attribute based on the value of the *SPEEDLIMIT* attribute.

3.2.1.2 Zoning designation

Zoning designation serves as a means of identifying locations within Redwood City that are more likely to correspond with an increase in biking. For example, cycling in and around mixed-use and destination (parks, schools, retail, dining, etc.) facilities is more preferable to cycling in and around industrial and single-family areas. Zoning, and its derivative, destinations, was used as an input factor in some of the reviewed bikeability studies (McNeil 2011; Olgun 2020; Porter et al. 2020; Winters et al. 2013).

The zoning dataset was downloaded from the Redwood City Open Data Portal website (Redwood City GIS n.d.) in polygon format and added to the ArcGIS Pro project file where it was projected. A new field was added in the attribute table and was titled *GeneralizedZone*. This was done because the Redwood City zoning code has 38 unique designations and for the purpose of this project, the number of zoning designations was simplified. This is also in alignment with literature that generalizes zoning to identify destinations of interest (McNeil 2011). The generalized zoning designations created for this project are industrial, single-family homes, multi-family homes, destination (commercial, office, parks, schools, etc.), and mixed-use. The new field was calculated using the following Arcade script:

$$
\begin{gathered}
var\ z\ =\ \$feature.ZONING \\
var\ gz\ =\ when(z\ ==\ 'RH', 'Single\ Family', z\ ==\ 'R-1', 'Single\ Family', \\
z\ ==\ 'R-2',\ 'Single\ Family', z\ ==\ 'RG',\ 'Single\ Family', \\
z\ ==\ 'R-3',\ 'Multi\ Family', z\ ==\ 'R-4',\ 'Multi\ Family', \\
z\ ==\ 'R-5',\ 'Multi\ Family', z\ ==\ 'PO',\ 'Destination', \\
z\ ==\ 'CA',\ 'Destination', z\ ==\ 'CN',\ 'Destination', \\
z\ ==\ 'CB',\ 'Destination', z\ ==\ 'CG',\ 'Destination', \\
z\ ==\ 'CP',\ 'Destination', z\ ==\ 'CO',\ 'Destination', \\
z\ ==\ 'IR',\ 'Industrial', z\ ==\ 'LII',\ 'Industrial', \\
z\ ==\ 'IP',\ 'Industrial', z\ ==\ 'GI',\ 'Industrial', z \\
==\ 'TP',\ 'Industrial', z\ ==\ 'AG',\ 'Industrial', \\
z\ ==\ 'IS',\ 'Industrial', z\ ==\ 'PF',\ 'Destination',
\end{gathered}
\tag{2}
$$

$$z\ ==\ 'MH',\ 'Single\ Family', z\ ==\ 'CBR',\ 'Destination',$$
$$z\ ==\ 'MUC-ECR',\ 'Mixed\ Use', z\ ==\ 'MUC-VB',\ 'Mixed\ Use',$$
$$z\ ==\ 'MUC-RC',\ 'Mixed\ Use', z\ ==\ 'MUC-SB',\ 'Mixed\ Use',$$
$$z\ ==\ 'MUC-GB',\ 'Mixed\ Use', z\ ==\ 'MUN',\ 'Mixed\ Use',$$
$$z\ ==\ 'MUT','Mixed\ Use', z\ ==\ 'MUW','Mixed\ Use','CUST')$$
$$return\ gz;$$

where *z* refers to the zoning attribute of the zoning polygon feature as set by *$feature.ZONING* and *gz* represents the new generalized zoning classification of the zoning polygon feature, dependent on the value of *z*. The script instructs ArcGIS Pro to iterate over the features in zoning polygon dataset and assigns values to the *GeneralizedZone* attribute based on the value of the *ZONING* attribute.

The zoning data was linked to the roads data using a spatial join to associate each road segment with a single zone value. In the *Spatial Join* tool configuration pane, the target feature was the *BikeabilityVariables* feature layer. The join feature was the zoning polygon dataset. The intersect match option was used with a search radius of 100 feet. In the fields section, a new field in the *BikeabilityVariables* layer was created titled *GenZone* and was set equal to the *GeneralizedZone* field from the zoning layer. The tool was run, and the result was a single zoning designation for each road segment. Of the 2,920 road segments, 26 of them had null values under *GenZone*. These null values were manually replaced with accurate zoning information based on visual observation.

The generalized zone attributes were converted from a text format into numeric values to fit the one to 10 scale. A new field called *Zone_Value* was created in the *BikeabilityVariables* feature layer attribute table and contained numeric values, each of which was associated with a generalized zoning category as per Table 4. Mixed-use and destination facilities are the most conducive to bikeability, which is why they were assigned scores of nine and 10 respectively.

Residential areas are moderately conducive to bikeability, with multi-family housing being slightly more conducive to bikeability than single-family housing. Industrial land uses are the least conducive to bikeability.

Table 4. Zoning designation reclassification

Raw Value	Reclassified Value	Scaled Value
Destination	1	9
Industrial	2	1
Single Family	3	4
Mixed Use	4	10
Multi Family	5	6

To reclassify the values, the newly created *Zone_Value* attribute was calculated using the following Arcade script:

$$\begin{gathered} var\ x\ =\ \$feature.GenZone \\ var\ nx\ =\ when(x\ ==\ 'Destination', 9, x\ ==\ 'Industrial', 1, \\ x\ ==\ 'Single\ Family', 4, \\ x\ ==\ 'Mixed\ Use', 10, \\ x\ ==\ 'Multi\ Family', 6, 'NONE') \\ return\ nx \end{gathered} \tag{3}$$

where *x* refers to the generalized zone attribute of the road segment as set by *$feature.GenZone* and *nx* represents the new zoning classification of the road feature, dependent on the value of *x*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and assigns values to the *Zone_Value* attribute based on the value of the *GenZone* attribute.

3.2.1.3 Slope

Slope was selected as an input variable as the slope of the road or bike lane has a significant impact on the amount of use the infrastructure can be expected to receive. Biking is most efficient on a flat surface and if the slope is too steep, it is possible that certain individuals would be unable or unwilling to cycle. Slope was also used as an input factor in some of the reviewed bikeability studies (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Krenn, Oja, and Titze 2015; Olgun 2020; Winters et al. 2013).

A DEM with 10m spatial resolution that encompassed the study area was downloaded from the United States Geological Survey website (National Map n.d.), added to the ArcGIS Pro project file, and projected. The DEM was clipped to the Redwood City boundary. The *Slope* geoprocessing tool was configured with the DEM as the input to produce the slope layer. The *Slope* tool was run and a raster layer covering the study area where each pixel contained a value representing the mean slope of that pixel in degrees was generated.

To assign each road segment line with a slope value, the *Add Surface Information* geoprocessing tool was used. The input feature was the *BikeabilityVariables* feature layer, and the input surface was the slope raster. The output property was set to average slope. The tool was then run and resulted in the creation of a new field within the road segment attribute table. This field was titled *Avg_Slope* and featured a numeric value representing the average slope along the associated road segment.

The slope values were reclassified from a range of zero to 90 degrees to fit within the scaled value range. A new field was created in the *BikeabilityVariables* attribute table and titled *Slope_Value*. This field hosted the scaled values (see Table 5). Literature has suggested that a slope of more than five degrees is uncomfortable for cyclists and a slope of more than 10 degrees is nearly impossible for the average biker (Olgun 2020). The scaled values selected for the slope input variable reflect these conclusions.

Table 5. Slope reclassification

Raw Value (slope in degrees)	Reclassified Value	Scaled Value
10-90	1	1
5-10	5	5
1.5-5	8	8
0-1.5	10	10

To reclassify the values, the newly created *Slope_Value* attribute was calculated using the following Arcade script:

$$\begin{gathered} var\ x\ =\ \$feature.Avg\_Slope \\ var\ nx\ =\ when(x\ <\ 1.5, 10, \\ x\ \geq\ 1.5\ \&\&\ x\ <\ 5, 8, \\ x\ \geq\ 5\ \&\&\ x\ <\ 10, 5, \\ x\ >=\ 10, 1, 'NONE') \\ return\ nx \end{gathered} \tag{4}$$

where *x* refers to the slope attribute of the road segment as set by *$feature.Avg_Slope* and *nx* represents the new slope classification of the road feature, dependent on the value of *x*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and assigns values to the *Slope_Value* attribute based on the value of the *Avg_Slope* attribute.

3.2.1.4 Tree canopy

Tree canopy was selected as an input variable for two reasons. First, a strong tree canopy implies an abundance of shade, which can help keep cyclists cool when they are biking during high temperatures. Second, exposure to trees, and nature in general, boosts the aesthetic of biking and makes it a more enjoyable experience. Tree canopy was used as an input variable in some of the reviewed bikeability studies (Arellana et al. 2020; Grigore et al. 2019; Krenn, Oja, and Titze 2015; Olgun 2020; Porter et al. 2020).

The NLCD 2016 US Forest Service Tree Canopy Cover was downloaded from the Multi-Resolution Land Characteristics Consortium website (MRLC Data n.d.) at a spatial resolution of 30m and added to the ArcGIS Pro project file before being projected and clipped. Each pixel in the raster contained a single value that represents the percentage of tree canopy coverage within that pixel.

To assign each road segment line with a tree cover value, the *Add Surface Information* geoprocessing tool was used. The input feature was the *BikeabilityVariables* feature layer and the input surface was the tree cover raster. The output property was set to “Mean Z”, which in this instance is average tree coverage percentage of each pixel. This resulted in the creation of a new field within the road segment attribute table. This field was titled *Z_Mean* and featured a numeric value representing the average tree coverage percentage along the associated road segment. The field name was immediately changed to *TreeCanopy* to avoid later confusion.

The tree canopy values were reclassified from a range of one to 10 to fit within the scaled value range. A new field was created in the *BikeabilityVariables* feature layer attribute table and titled *TC_Value*. This field hosted the scaled values, which are visible in Table 6.

Table 6. Tree canopy reclassification

Raw Value (Tree Canopy Percentage)	Reclassified Value	Scaled Value
0-10%	1	3
10-20%	2	4
20-30%	3	5
30-40%	4	6
40-50%	5	7
50-60%	6	8

To reclassify the values, the newly created *TC_Value* attribute was calculated using the following Arcade script:

$$
\begin{gathered}
var\ x\ =\ \$feature.TreeCanopy \\
var\ nx\ =\ When(x\ <\ 10, 3, x\ \geq\ 10\ \&\&\ x\ <\ 20, 4, \\
x\ \geq\ 20\ \&\&\ x\ <\ 30, 5, X\ \geq\ 30\ \&\&\ x\ <\ 40, 6, \\
x\ \geq\ 40\ \&\&\ x\ <\ 50, 7, x\ \geq\ 50\ \&\&\ x\ <\ 60, 8, \\
x\ \geq\ 60, 9, 'NONE') \\
return\ nx
\end{gathered} \tag{5}
$$

where *x* refers to the tree canopy attribute of the road segment as set by *$feature.TreeCanopy* and *nx* represents the new tree canopy classification of the road feature, dependent on the value of *x*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and assigns values to the *TC_Value* attribute based on the value of the *TreeCanopy* attribute.

3.2.1.5 Bike lane access

The existence of and ease of access to bike lanes is an important variable in quantifying bikeability. If bike lanes are sparce and difficult to access, ridership will inevitably be low. Bike lane access was used as an input variable in some of the reviewed bikeability studies (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Krenn, Oja, and Titze 2015; Porter et al. 2020; Winters et al. 2013).

Developing data to represent bike lane access required more analytical and preparatory work than the other five variables. The existing and proposed bike lane data were retrieved from the Redwood City WBTI website as a KML file. Upon addition to the ArcGIS Pro project file, the layer was input into the *Feature Class to Feature Class* geoprocessing tool to allow for modifications and the output layer was projected. The downloaded data did not feature explicit attributes that distinguished between class or between whether a bike lane was existing or proposed. Instead, each lane was assigned an ID value that could be used to identify the class and status. However, to improve legibility of the layer, two new fields were added: *Lane_Class* (I, II, III, or IV) and *Status* (existing or proposed). The lane class field was calculated using the following Arcade script:

$$
\begin{gathered}
var\ id\ =\ \$feature.SymbolID \\
var\ class\ =\ when(id\ ==\ 0,'Class\ I', \\
id\ ==\ 1,\ 'Class\ II', \\
id\ ==\ 2,\ 'Class\ III', \\
id\ ==\ 3,\ 'Class\ IV', \\
id\ ==\ 4,\ 'Class\ I', \\
id\ ==\ 5,\ 'Class\ II', \\
id\ ==\ 6,\ 'Class\ III', \\
id\ ==\ 7,'Class\ IV','a') \\
return\ class;
\end{gathered} \tag{6}
$$

where *id* refers to the bike lane class and status attribute of the bike lane feature as set by *$feature.SymbolID* and *class* represents the new bike lane class value of the bike lane feature, dependent on the value of *id*. The script instructs ArcGIS Pro to iterate over the features in the bike lane dataset and assigns values to the *Lane_Class* attribute based on the value of the *SymbolID* attribute.

The lane status field was calculated using the following Arcade script:

$$
\begin{gathered}
var\ id\ =\ \$feature.SymbolID \\
var\ class\ =\ when(id\ ==\ 0,'2022', \\
id\ ==\ 1,\ '2022', \\
id\ ==\ 2,\ '2022', \\
id\ ==\ 3,\ '2022', \\
id\ ==\ 4,\ 'Proposed', \\
id\ ==\ 5,\ 'Proposed', \\
id\ ==\ 6,\ 'Proposed', \\
id\ ==\ 7,'Proposed','a') \\
return\ class;
\end{gathered} \tag{7}
$$

where *id* refers to the bike lane class and status attribute of the bike lane feature as set by *$feature.SymbolID* and *class* represents the new bike lane status value of the bike lane feature, dependent on the value of *id*. The script instructs ArcGIS Pro to iterate over the features in the bike lane dataset and assigns values to the *Status* attribute based on the value of the *SymbolID* attribute.

The bike lane access attribute information describes whether a road segment is within 200m of a bike lane or not. 200m was chosen based on similar scenarios in the investigated literature (Winters et al. 2013). Cyclists may be dissuaded to bike if they are required to travel significantly further to get to safe infrastructure. There are four possible values for this attribute: Class I/IV, Class II, Class III, and none. Classes I and IV were combined as they both provide physical separation from the road for cyclists, the only difference being that Class I bike lanes do not follow existing roads while Class IV bike lanes are adjacent to existing roads. If a road segment is within 200m of multiple lane classes, the value would be determined by the highest-ranking class (Classes I and IV are the best, followed by Class II and then Class III). The bike lane access calculations were performed using two separate *ModelBuilder* tools.

To determine which street segments were within 200m of a bike lane, a *ModelBuilder* tool (Figure 13) was created and ran four times, once for each bike lane class. First, the *Polyline to Raster* geoprocessing tool was used to convert a road segment polyline layer into a raster layer. The cell size was set to 1 foot to minimize the effects of using a raster representation of streets rather than a polyline representation. The *Path Distance* tool was then used. The input feature data was the bike lane layer (Class I, II, III, or IV) and the input cost raster was the output of the *Polyline to Raster* geoprocessing tool. The maximum distance was set equal to 656.168 feet, as this is equal to 200m. The result of the *Path Distance* tool was a new raster layer where each cell contained a value that described how far it was from the bike lanes. Cells from the original street segment raster layer that were further than 200m from the bike lane were eliminated from the *Path Distance* tool output. The *Reclassify* tool was then used to convert each cell value from its respective distance value to a value of one to score all cells within 200m of a bike lane equally. The reclassified raster layer was then used as the input raster in the *Raster to Polygon* geoprocessing tool. The polygonal output layer was then used in the *Select Layer by Location* geoprocessing tool, where the input feature was the *BikeabilityVariables* (shown as *SJ_Zoning* in Figure 13) layer and the relationship was set to intersect. The layer with selection was then input into the *Copy Features* geoprocessing tool, which created a new line dataset containing all road segments within 200m of the specified bike lane class. The *ModelBuilder* was run a total of four times, with the only alteration for each run being the bike lane layer input in the *Path Distance* tool. The end result was four new line layers: road segments within 200m of Class I bike lanes, road segments within 200m of Class II bike lanes, road segments within 200m of Class III bike lanes, and road segments within 200m of Class IV bike lanes. The Class I layer and Class IV layer were merged together as both refer to similar infrastructure types with full physical protection for cyclists from cars.

Figure 13. Bike lane access *ModelBuilder* layout

Next, the four separate line layers were combined into a single layer where each road segment was assigned a lane class, or "none," dependent on its spatial relationship with existing cycling infrastructure. This was done using a *ModelBuilder* tool (Figure 14). The *Erase* geoprocessing tool was used to erase Class II road segments from Class III road segments. The resulting output, titled *Class III Erase*, was then used as the input feature in another *Erase* geoprocessing tool, where the erase feature was the Class I/IV road segment layer. Simultaneously, the Class I/IV layer was erased from the Class II layer, resulting in an output titled *Class II Erase*. *Class III Erase*, *Class II Erase* and the Class I/IV layer were all merged, resulting in a street segment layer where each segment that was within 200m of a bike lane had a lane class value listed under the newly created field, *BLAClass*. The merged layer was then erased from a layer of all street segments within the study area. This resulted in a layer of street segments that were over 200m from any class of bike lane. This layer was then merged with the bike lane merge layer. A spatial join was then conducted to attach the *BLAClass* attribute to the *BikeabilityVariables* feature layer. While street segments within 200m of a bike lane had a value for the *BLAClass* attribute, those that were further than 200m had a null value. This was changed to a value of “None” using the following Arcade script in the *Calculate Field* tool:

$$\begin{gathered} var\ b\ =\ \$feature.BLAClass \\ var\ nb\ =\ when(b\ ==\ 'Class\ I/IV','Class\ I/IV', \\ b\ ==\ 'Class\ II',\ 'Class\ II', \\ b\ ==\ 'Class\ III','Class\ III','None') \\ return\ nb \end{gathered} \tag{8}$$

where *b* refers to the bike lane class attribute of the road segment as set by *$feature.BLAClass*, and *nb* represents the new bike lane class value of the bike lane, dependent on the value of *b*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and if a road segment has a null bike lane class attribute value, it is assigned “None”.

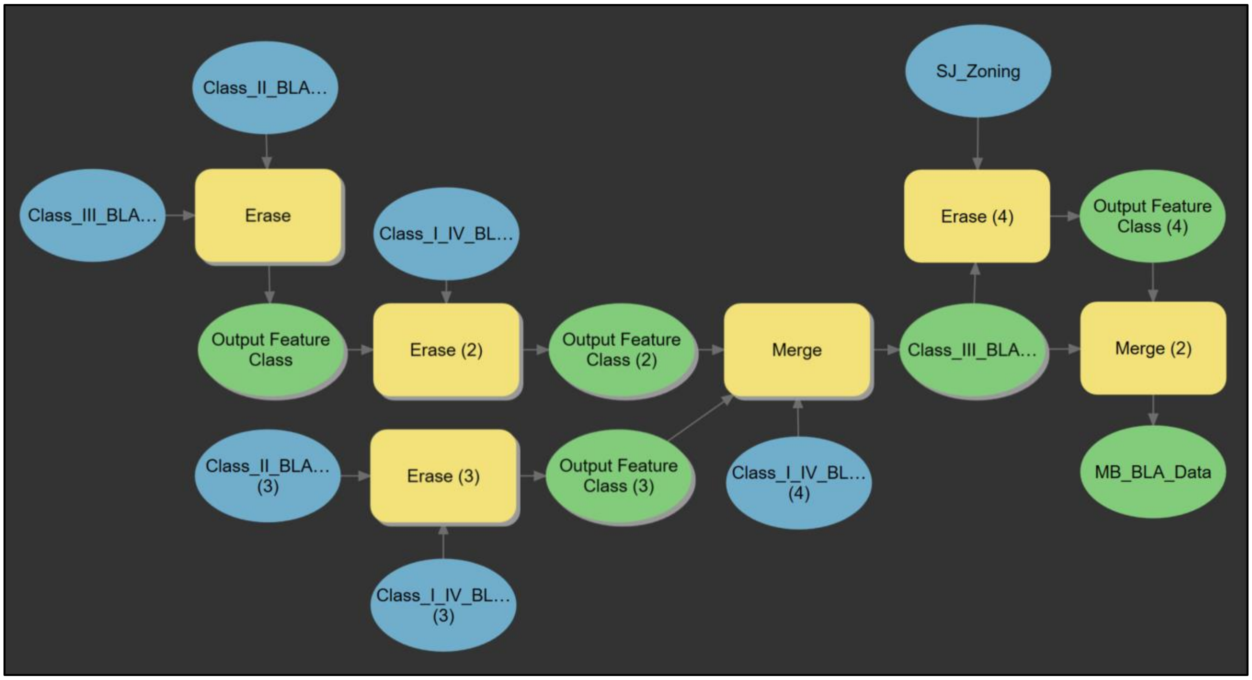


Figure 14. Bike lane access merge *ModelBuilder* layout

At this point, the bike lane access attribute was in text form and had to be reclassified to fit within the scaled value range. A new field was created in the *BikeabilityVariables* feature layer attribute table and titled *BLA_Value*. This field hosted the scaled values, which are visible in Table 7. The scaled values take into account the level of comfort of using each of the four bike lane access scores. Class I and IV bike lanes are ideal and were scaled to a value of nine. Class II bike lanes are moderately attractive options and were scaled to a value of 5. Class III bike lanes and road segments that were further than 200m of any bike lane were scaled to low values, as these road segments are not very conducive to high bikeability.

Table 7. Bike lane access reclassification

Raw Value (Bike Lane Access)	Reclassified Value	Scaled Value
200m of C1 & C4	Class I/IV	9
200m of C2	Class II	5
200m of C3	Class III	3
>200m from any	None	1

To reclassify the values, the newly created *BLA_Value* attribute was calculated using the following Arcade script:

$$\begin{gathered} var\ x\ =\ \$feature.BLAClass \\ var\ nx\ =\ When(x\ ==\ 'Class\ I/IV', 9, \\ x\ ==\ 'Class\ II', 5, \\ x\ ==\ 'Class\ III', 3, \\ x\ ==\ 'None', 1, 'NONE') \\ return\ nx \end{gathered} \tag{9}$$

where *x* refers to the bike lane class attribute of the road segment as set by *$feature.BLAClass* and *nx* represents the new bike lane access classification of the road feature, dependent on the value of *x*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and assigns values to the *BLA_Value* attribute based on the value of the *BLAClass* attribute.

3.2.1.6 Crashes

Crash data serves as a means of representing the hazards of biking along a given street and to a lesser extent, the expected amount of traffic on a given street. Streets with a high amount of crashes are more dangerous and may incite more interactions between cyclists and drivers. While crashes were not explicitly used as an input in the reviewed studies, hazards and traffic counts were (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Grisé and El-Geneidy 2018), both of which can be partially represented by crash statistics.

A point dataset was downloaded from the University of California, Berkeley Transportation Injury Mapping System website (Transportation Injury Mapping System n.d.) that contains point data of traffic accidents. The data was filtered so that only crash points within San Mateo County between March 2015 and March 2020 where a cyclist was involved were downloaded. This temporal scale was chosen as it was still relatively recent, but also protected against reduced traffic and crash numbers as a result of the COVID-19 pandemic. The point data was added to the ArcGIS Pro project file and was projected. The data was then clipped using the Redwood City boundary polygon layer.

Next, a relationship between the crash point data and the road line segment data had to be created. A 40-foot buffer was created around each road segment using the *Buffer* geoprocessing tool. This ensured that all points along roadways would be included and that in the case of a crash at an intersection, both intersecting roads would be considered as the location of a crash. The *Aggregate Points* tool was used to sum the number of crash points within each road segment buffer polygon. A *Join* function with the completely within join operation was used to join the sum of crashes within each buffer with the *BikeabilityVariables* feature layer. This was done in a new field called *Crashes* where each road segment's attribute was a value representing the number of cyclist-involved crashes along the road segment between March 2015 and March 2020. Next, the data was reclassified to the scaled values listed in Table 8. Road segments with zero crashes were scaled to a value of nine, because they have historically been safe streets for cyclists. However, a value of 10 was not given since the chance of a crash always exists. Road segments with five crashes were scaled to a value of three because while these segments represent what have historically been the most dangerous roads and intersections for cyclists over the past five years, one crash per year is not an alarming rate. As such, five-crash-segments were not assigned a value of one.

Table 8. Crashes reclassification

Raw Value (Number of Crashes)	Reclassified Value	Scaled Value
0	0	9
1	1	7
2	2	6
3	3	5
4	4	4
5	5	3

A new field was created in the *BikeabilityVariables* feature layer attribute table and titled *Crash_Value*. This field was calculated using the following Arcade script:

$$\begin{gathered} var\ x\ =\ \$feature.Crashes \\ var\ nx\ =\ When(x\ ==\ 0, 9, \\ x\ ==\ 1, 7, \\ x\ ==\ 2, 6, \\ x\ ==\ 3, 5, \\ x\ ==\ 4, 4, \\ x\ ==\ 5, 3, 'NONE') \\ return\ nx \end{gathered} \tag{10}$$

where *x* refers to the crash attribute of the road segment as set by *$feature.Crashes* and *nx* represents the new crash classification of the road feature, dependent on the value of *x*. The script instructs ArcGIS Pro to iterate over the features in the road segment dataset and assigns values to the *Crash_Value* attribute based on the value of the *Crashes* attribute.

3.2.2 Weighted Sum to Quantify Bikeability

To quantify bikeability, a weighted sum equation was used. The equation was applied to each individual road segment and combined the six input variables with their respective weights to output a single number that represented the bikeability of that particular road segment.

A new text field was created on the *BikeabilityVariables* feature layer and titled *Bikeability*. This field was calculated using a weighted sum methodology within the *Calculate Field* tool. Each of the six input variables was assigned a weight as per Table 9. The weights for this project roughly follow weights used in previous literature (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Grisé and El-Geneidy 2018; Krenn, Oja, and Titze 2015; Porter et al. 2020; Winters et al. 2013). For example, many previous studies allotted higher weights to existing bike lane access and slope as opposed to other input variables. Certain variables have more of an impact on bikeability than others and that is reflected in the weights selected for this analysis.

Table 9. Bikeability weights

Variable	Weight
Speed Limit	15%
Zone	15%
Slope	20%
Tree Canopy	8%
Bike Lane Access	30%
Crashes	12%
Total	100%

For each road segment, each reclassified variable score was multiplied by its weight. Each of these six multiplications were then added together, resulting in a final bikeability score within the range of one to 10. The calculation was performed using the following Arcade script:

$$
\begin{gathered}
var\ bikeability = \ (ValSpeedLimit * 0.15) \\
+ (ValGenZone * 0.15) \\
+ (ValSlope * 0.20) \\
+ (ValTreeCanopy * 0.08) \\
+ (ValBLAClass * 0.30) \\
+ (ValCrashes * 0.12) \\
return\ bikeability
\end{gathered} \tag{11}
$$

where *bikeability* represents the bikeability score of a road segment, *ValSpeedLimit* represents the speed limit attribute of a road segment, *ValGenZone* represents the generalized zone attribute of a road segment, *ValSlope* represents the slope attribute of a road segment, *ValTreeCanopy* represents the tree canopy attribute of a road segment, *ValBLAClass* represents the bike lane access attribute of a road segment, and *ValCrashes* represents the crash attribute of a road segment. The numeric values which are used to multiply each respective attribute represent the overall weight of the associated attribute as it pertains to evaluating bikeability.

3.2.3 Reclassifying Bikeability for Site Selection

Bikeability scores were ultimately used in the final site selection process, which is outlined in section 3.5. To comply with the other site selection input variables which are outlined in sections 3.33.3.3 and 3.4, the bikeability scores were reclassified to a range of zero to four.

First, a new field was created within the proposed project polyline feature layer attribute table and was titled *Bikeability*. Because bikeability scores had previously been created for each street segment in Redwood City, it was only necessary to transfer the values into the proposed projects attribute table. However, because the proposed projects do not perfectly align with the street segments, it was necessary to use a *ModelBuilder* geoprocessing tool (Figure 15) to assign each proposed project with a bikeability score.

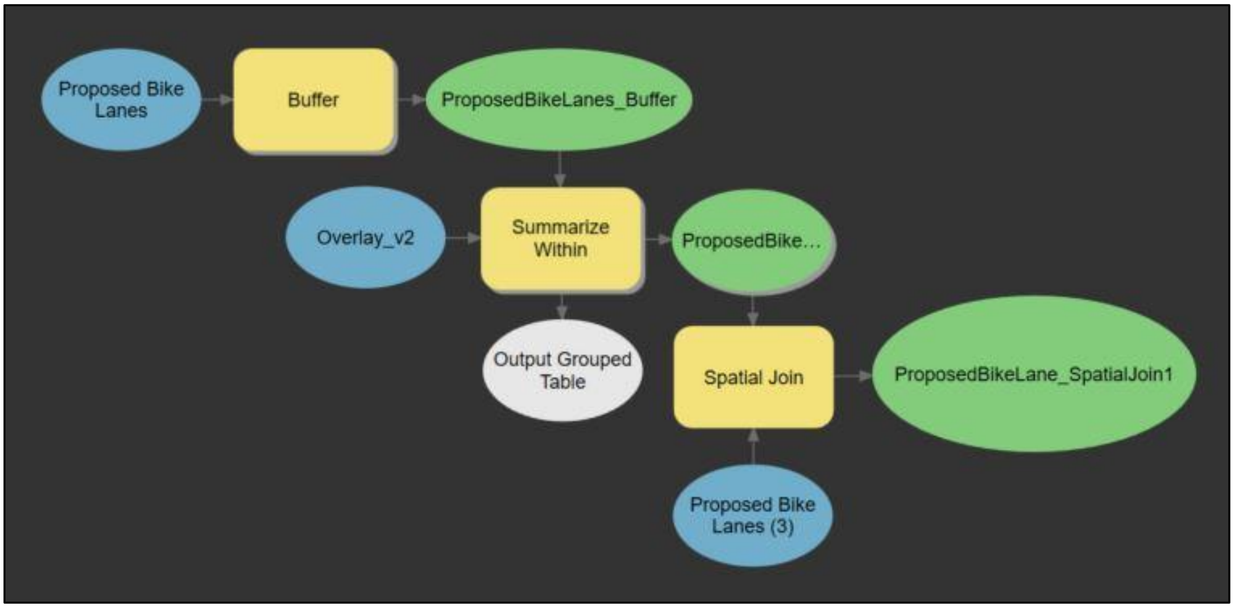


Figure 15. Proposed project bikeability *ModelBuilder* layout

The proposed bike lane layer was set as the input layer for the *Buffer* geoprocessing tool. A buffer distance of 50ft was used to ensure that proposed projects would not pick up on bikeability scores from parallel streets while also ensuring that small differences in the two polylines could be accounted for. The output buffer was then used as the input polygon in the *Summarize Within* tool. The dataset to be summarized was the bikeability attribute of the *BikeabilityVariables* feature layer (named *Overlay_v2* in Figure 15). The *Summarize Within* tool calculated the mean bikeability score of all road segments within each respective buffer polygon. The output was a polygon layer with an identical geographic extent as the buffer layer, but a new attribute of mean bikeability. A spatial join was then performed where the bikeability value of each polygon was joined to the proposed projects polyline feature layer using the completely within match option. The output of this was a polyline layer featuring each proposed project including a bikeability attribute value. This attribute value could then be joined to a new attribute field titled “MeanBikeability” in the proposed project feature layer using a common attribute, such as project name.

To execute the weighted sum function, it is necessary for each of the input variables to maintain an identical scale. Because the equity sum attribute value had a range of zero to four due to the use of four datasets of equity-related polygons, it was necessary to reclassify the bikeability values to be within this range. Furthermore, the bikeability values were inverted because in the context of project site selection, a lower bikeability score is more desirable; proposed projects that are in locations with poor bikeability as of 2022 should be prioritized over projects in locations with high bikeability. This reclassification was completed by first adding a new field titled *BikeReclass* and then calculating that field using the following Arcade script:

$$\begin{gathered} var\ BikeReclass\ =\ 4 \\ -\ ((\$feature.MeanBikeability\ *\ 4) \\ /\ 10) \\ return\ BikeReclass \end{gathered} \tag{12}$$

where *BikeReclass* is equal to the new reclassified bikeability attribute and *$feature.MeanBikeability* refers to the bikeability attribute of the proposed project layer.

3.2.4 Demographic Comparison

To gain insight into the relationship between bikeability and social demographic information in Redwood City, a methodology using light geospatial analysis and symbolization techniques was used.

After the bikeability layer was created, a demographic polygon layer was downloaded from the San Mateo County GIS open data portal (San Mateo County GIS n.d.). These layers were aggregated at the block group level and included a variety of attributes, including the percentage of households that did not own a car and median household income. First, the new layer was added to the ArcGIS Pro project file where it was projected and clipped to the Redwood City boundary polygon layer. The *Spatial Join* geoprocessing tool was used to add the average bikeability within each block group to the demographic attribute table. Bivariate symbology was then applied to the layer to visualize the relationship between bikeability and no-car households, bikeability and median household income, and bikeability and non-White percentage. A total of six maps were produced with three of them illustrating the demographic information in Redwood Shores and three of them illustrating the demographic information in the rest of Redwood City.

3.3 Workshop

A workshop was organized to solicit input from Redwood City residents on the current and future state of bikeability in the city. The workshop required the formation of a relationship with local government agencies and community stakeholders. Details on planning, execution, and post-workshop activities are described below.

3.3.1 Workshop Planning

To prove effective, the workshop had to be methodically planned out. It was critical that the materials of the workshop supported high-quality discussions and participation. Furthermore, planning was necessary to ensure that participants would attend the meeting.

Following initial conversations with Redwood City Mayor Giselle Hale, the workshop planning was initiated with Rafael Avendaño at the nonprofit organization Redwood City Together. This nonprofit works closely with the city and looks to improve issues of inequity in the city. One of their focuses is on improving bike safety, especially for children. Mayor Hale also connected the author with City Manager Melissa Stevenson Diaz, who proceeded to loop in

Transportation Manager Jessica Manzi. Ms. Manzi then brought WBTI Project Manager Malahat Owrang into the discussion. Ms. Owrang provided existing and proposed bike infrastructure spatial data.

Meanwhile, an initial email was sent to Mr. Avendaño of Redwood City Together to describe the thesis project and express desire to work together to plan a mutually beneficial workshop. Mr. Avendaño was receptive to the idea and set up a 45-minute meeting between the author, Mr. Avendaño, and Jackie Campos, who is the nonprofit's Safe Routes to School specialist.

In the meeting, Mr. Avendaño and Ms. Campos spoke about Redwood City Together and the organization's goals and methods. They also spoke about the ongoing Safe Routes to School project and why it is important that the city's youth have easy and efficient access to schools and parks via foot or bike. The author then discussed the project and geodesign methodology before outlining the importance of a workshop and explaining how it would be a mutually beneficial partnership. The author would be able to provide meaningful public feedback as well as GIS analysis while Redwood City Together and the City of Redwood City would help with participant outreach and planning. Ultimately, Mr. Avendaño and Ms. Campos were both interested in helping the author host a workshop, but it would first require confirmation from Redwood City Together Leadership Council members. The members would be attending the upcoming Safe Routes to School task force meeting, so Ms. Campos blocked out time in the agenda for the author to present the workshop idea and conduct a vote on whether or not the workshop would be confirmed.

At the Safe Routes to School task force meeting, there were approximately 20 attendees. The author was able to present the workshop proposal and Ms. Campos proceeded to poll the attendees about whether or not they approved of the proposal. All but one approved, which meant that the workshop was permitted to move forward. In the coming days, Ms. Campos and the author held a separate meeting with the one member who disapproved of the proposal to further discuss the workshop's purpose and methods. The member ultimately approved of the idea.

At this point, the workshop had been approved. Because of the nature of the workshop and the fact that the author would be interacting with human subjects and incorporating their responses into the project, Institutional Review Board (IRB) approval was deemed necessary. The author filled out the required paperwork to seek IRB approval through the University of Southern California (USC). The author also completed a required CITI Program module on performing a Social-Behavioral study on Human Subjects. The application was submitted for review. About one month later, it was determined that due to the nature of the workshop and the fact that all results would remain anonymous indefinitely, IRB approval was not needed and the workshop was ethically allowed to take place

For the next couple of months, the author met with Ms. Campos to advance the planning process of the workshop. This involved brainstorming the format, determining a date, and preparing methods of participant outreach.

Ultimately, it was determined that the workshop would take place on February 23, 2023 over Zoom. The author originally planned to have an in-person workshop, but the decision was made to host it online in part due to the ongoing COVID-19 pandemic. Outreach and the development of final workshop materials began in early February. Ms. Campos spearheaded the outreach and contacted several Redwood City Together connections as well as local schools and cyclist groups. She also created a flier with workshop information that was distributed to mailing lists (Figure 16) as well as an Eventbrite site where interested individuals could RSVP and receive a Zoom link.

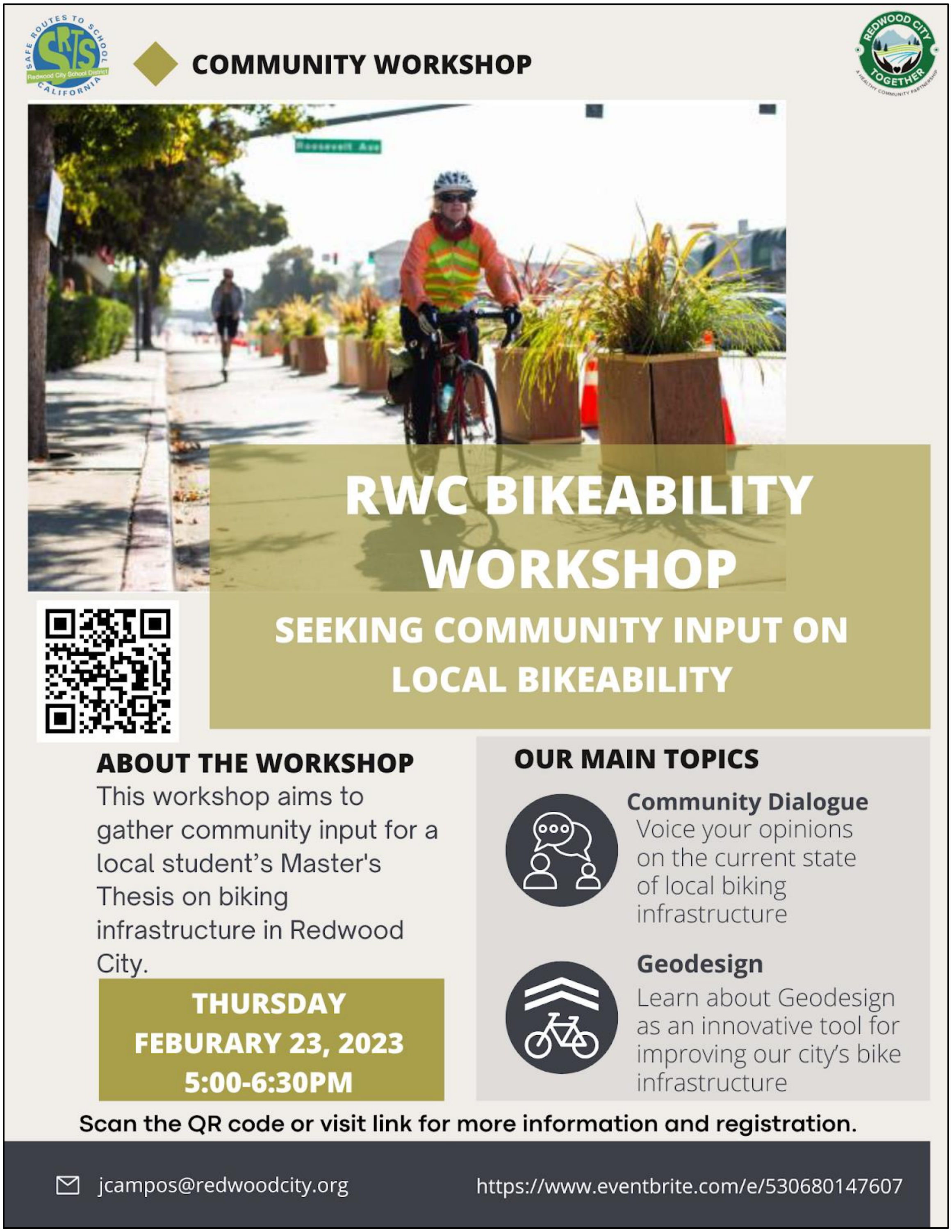


Figure 16. Workshop outreach flier.

The author also engaged in the outreach process, speaking at the February Safe Routes to School task force meeting and sharing a brief slideshow with information about the workshop. Participants of this meeting were invited to the workshop.

The author created content to be used in the workshop. The first deliverable was a slideshow, created in Google Slides. The slideshow began with a brief introduction of the author, a workshop agenda, and housekeeping items related to maintaining anonymity in participant responses. Next, the discussion shifted to cover the topic of bikeability and why it is critical that cities adopt improved cycling infrastructure. The presentation then transitioned to a more focused discussion on cycling in Redwood City, showing images of the four classes of bike lanes as well as maps of bikeability as of 2022. The introductory presentation ended by talking about problems and solutions facing bikeability in Redwood City as well as outlining the work the city has already done through the WBTI. The next couple of slides included links to the survey and Miro boards, which served as the interactive components of the workshop. Following the activities, the presentation would resume, first by allowing the present members of the Redwood City Team of the Silicon Valley Bicycle Coalition to show a slide and speak about their group. The author then completed the workshop by displaying two concluding slides that summarized the workshop and offered some final thoughts on bikeability.

The Google Form was created and incorporated questions that were designed to elicit responses about the participants' experiences cycling in Redwood City as well as what they would like to see in the future in terms of bike infrastructure. There was a total of eight questions, which are listed in Table 10.

Table 10. Workshop survey questions

Question	Answer Format
How important is living in a bikeable city to you? (Select one)	Not important, minimally important, neutral, important, very important
Do you ride a bike? If so, how often?	Free response
If you cycle, what are your reasons for doing so? (Select all that apply)	I don't bike, work or school, errands, exercise, pleasure, to get outdoors, other (free response)
What do you see as barriers to biking more in Redwood City? (unprotected lanes, fast drivers, inconvenient, lack of storage facilities/bike parking etc.)	Free response
What are some variables besides bike infrastructure that would make you more likely to cycle? (More trees, more mixed-use zoning, etc.)	Free response
Select all infrastructure types you would like to see in Redwood City. (Select all that apply)	Images of: physical lane separation, bollard lane separation, integrated roundabouts, conventional bike lanes, other (free response)
If more bike infrastructure was built, which classes of lane would you be willing to use? (Select all that apply)	Class I, Class II, Class III, Class IV, none
Do you have any other comments to make about bikeability in Redwood City?	Free response

Miro was selected as the interface to allow participants to engage in an interactive mapping activity. Miro is an online application which serves as a virtual whiteboard, allowing users to add text, images, drawings, and shapes. A user can create multiple documents, also known as Miro boards, and share these boards with other users who can then simultaneously collaborate in the virtual space. Three activities were created, each on their own Miro board. The activities were meant to foster collaboration, so three copies of each activity were created on each board and each board would be used by a group of participants who would be placed in a breakout room.

The first activity allowed participants to draw locations on a map of Redwood City that they considered dangerous to pedestrians and cyclists (Figure 17). On each Miro board, there was space below each interactive map where participants could use the sticky note tool to leave comments explaining their decisions.

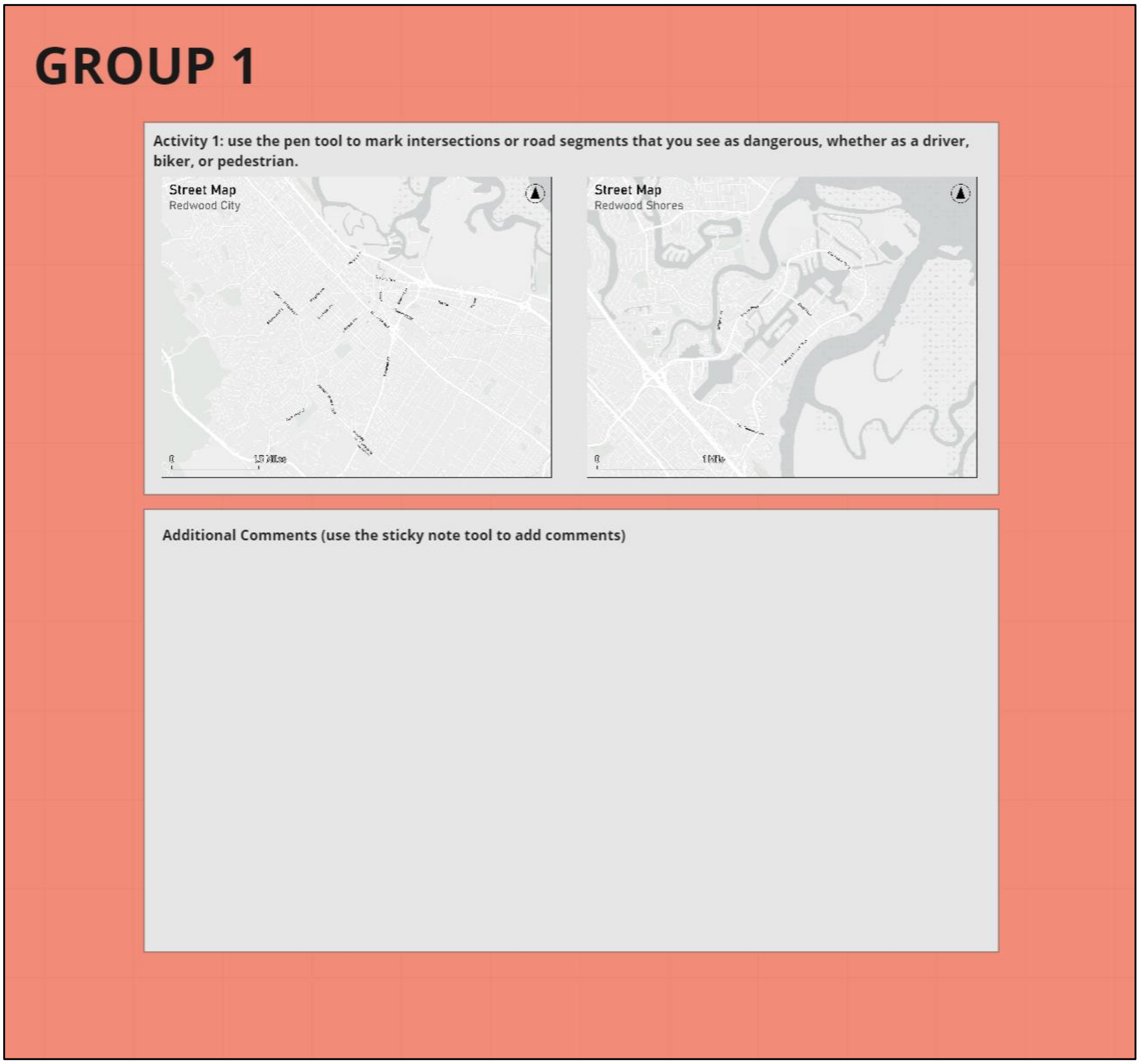


Figure 17. Activity 1 Miro board

The second activity allowed participants to draw out their dream cycling network, indicating on the map where they would like to see improved infrastructure (Figure 18).

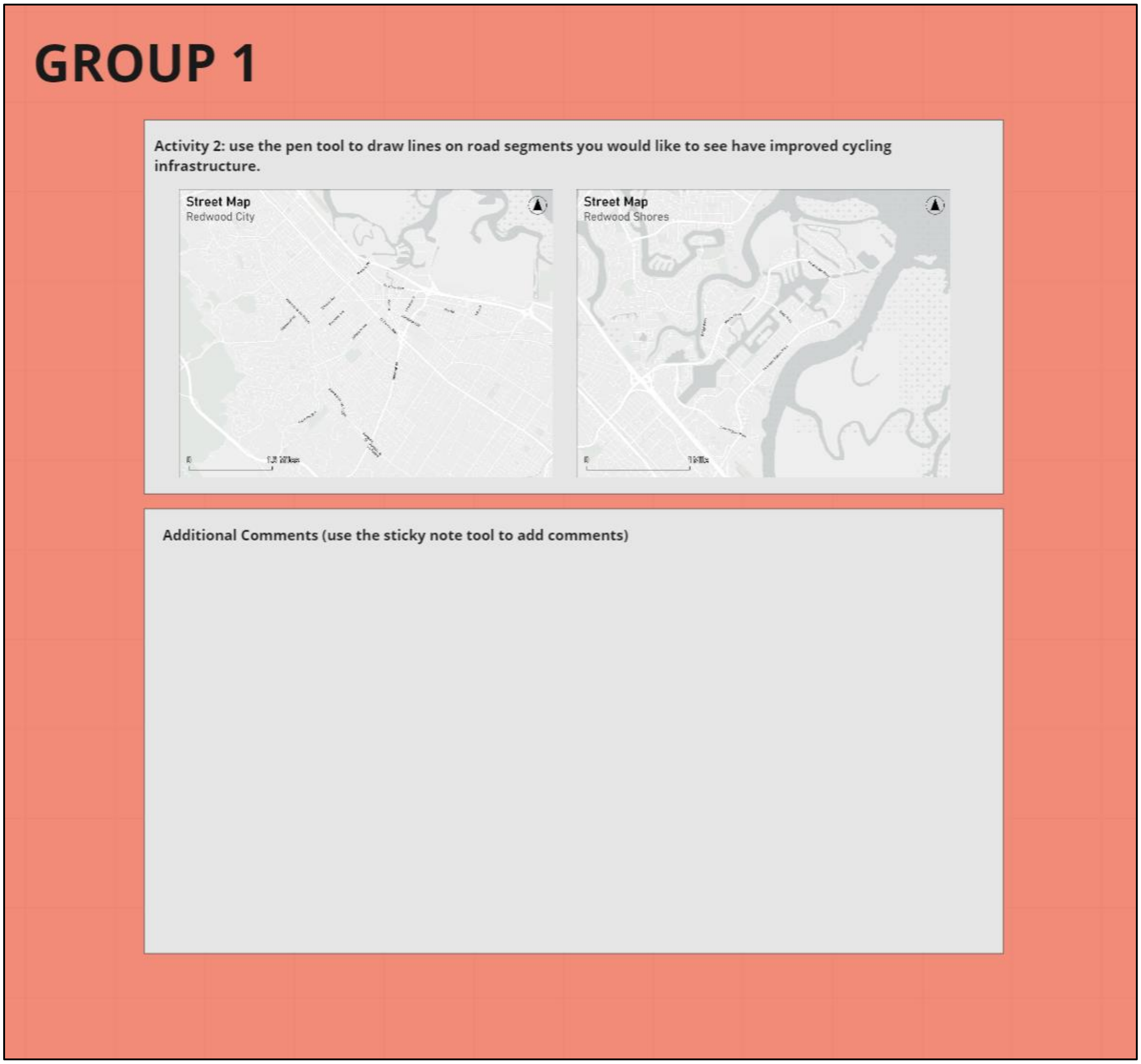


Figure 18. Activity 2 Miro board

The third activity asked participants to select their top three proposed projects and indicate which they would most like to see be implemented (Figure 19).

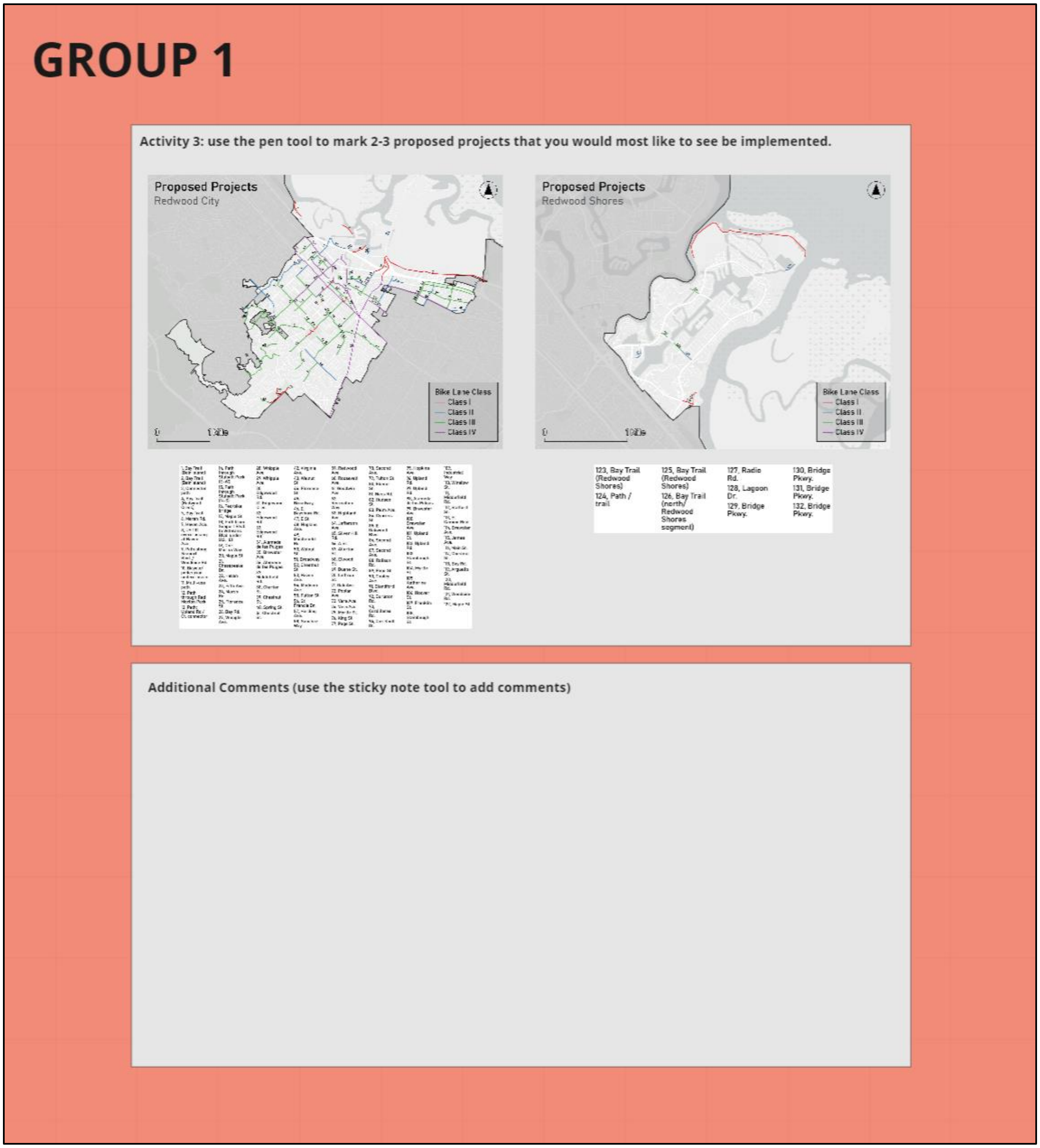


Figure 19. Activity 3 Miro board

3.3.2 Conducting the Workshop

The workshop took place from 5:00pm to 6:30pm on Thursday, February 23, 2023. It included a slide deck presentation, survey, and interactive and collaborative mapping exercise.

Twenty participants RSVP'd for the workshop, yet only 11 attended. The workshop went smoothly. It started right at 5pm and began with the presentation outlined in section 3.3.1. Next, participants were asked to complete the Google Survey, of which the link was provided in the Zoom chat. Participants were given 10 minutes to complete the survey and were instructed that because this may be more time than necessary, extra time could be used as a bathroom, food, or water break. Upon completion of the survey, the interactive activities began. The link to the first Miro board was provided and participants were split into breakout rooms. Because two participants left the workshop early, the nine remaining participants were split into three groups of three participants. The groups were instructed to draw on their own board and delegate one drawer to minimize chaos on the Miro board. Groups were given 10 minutes to discuss their responses to the prompt and draw out their conclusions. After the 10 minutes was up, the author facilitated a 10-minute discussion where participants could explain their decisions and drawings and also comment on other group's conclusions. This process was repeated two more times for the final two Miro boards.

Following the activities, the presentation was resumed, and the Redwood City Team of the Silicon Valley Bicycle Coalition provided some information about their organization. The author then made concluding remarks and thanked the participants for their attendance. The workshop ultimately ran five minutes over the allotted time, ending at 6:35pm.

3.3.3 Assessment of Workshop Results

The goal of the workshop was to obtain public comments on the current and future state of cycling in Redwood City as well as determine which of the city's 132 proposed bike infrastructure projects were most popular. The content created by workshop attendees was synthesized and organized for the purposes of selecting a cohort of proposals to move forward in this project's geodesign workflow.

The author reviewed the Zoom recording and created a Google Sheet document to list each street or proposed project that was mentioned either in the survey, on the Miro board, or in verbal discussion. Each street or proposed project that was mentioned was listed on the sheet in a column. There were 16 total streets and two proposed projects mentioned. Of the 16 mentioned streets, two of them did not have any associated proposed projects and they were discarded. An additional column was filled out with the proposed project labels (project number and name) input next to each associated street. In some cases, a mentioned street had multiple proposed projects along it and new proposed project rows were added to accommodate this. After extracting the proposed projects from the mentioned streets and listing them along with the two directly mentioned in the workshop, there was a total of 24 proposed projects referred to either directly or indirectly during the workshop (Table 11). Next, a column of values representing the number of mentions for each street or proposed project was added. Another column was added to indicate the number of positive mentions for each street or proposed project. Of the 24 proposed projects, only two did not have 100 percent positive mentions.

Table 11. Proposed projects mentioned during the workshop

Proposed Projects Mentioned
34 – Alameda de las Pulgas
36 – Alameda de las Pulgas
98 – Alameda de las Pulgas
119 – Arguello St.
113 – El Camino Real
82 – Hudson St.
64 – Jefferson Ave.
54 – Madison Ave.
17 - Maple St.
20 – Maple St.
122 – Maple St.
37 – Middlefield Rd.
49 – Middlefield Rd.
111 – Middlefield Rd.
120 – Middlefield Rd.
75 – Myrtle St.
18 – Path from Seaport Blvd. to Veterans Blvd. under U.S. 101
12 – Path through Red Morton Park
72 – Poplar Ave.
59 – Redwood Ave.
60 – Roosevelt Ave.
73 – Vera Ave.
74 – Vera Ave.
121 – Woodside Rd.

In addition to naming specific streets that could benefit from improved cycling infrastructure, the participants generally agreed on two main considerations that should be kept in mind when planning out Redwood City's future bike network. First, when possible, arterial cycling routes should be created to serve as safe routes across the entirety of the city as well as to maximize the efficiency of bike routes and avoid irregular patterns in the network. Second, implementing cycling infrastructure near schools and parks should be prioritized over other locations to increase bike safety and accessibility for the most vulnerable cyclists in the city. Participants also voiced that this would be a good way to inspire the next generation of Redwood City residents to adopt cycling as a main form of transportation.

To accommodate the public's desire for new cycling infrastructure being implemented near parks and schools, a new attribute field titled *ParksSchools* was added to the proposed projects dataset. A dataset downloaded from the San Mateo County GIS data hub website (Information Services n.d.) that featured polygons of all the schools and parks in San Mateo County was added to the ArcGIS Pro project file. A 500ft buffer was then added to this layer using the *Buffer* geoprocessing tool. The *Select Within* tool was used to select all proposed projects that were at least partially within the buffer layer. All of the selected proposed projects were assigned a value of one in the data table, while those outside of the buffer zone were assigned a value of zero. The Google Sheet column delineating whether a street or proposed project was near a school or park could then be filled out by cross checking each proposed project with the new attribute field values. In the Google Sheet, proposed projects near schools and parks were given a value of one while proposed projects not near schools and parks were given a value of zero.

At this point, a final score that quantified the needs of the residents could be computed. This was done for each of the 24 proposed projects and was done in a manner to ensure that all scores would be within the range of zero and four. Each mention of the street or proposed project after the initial mention would add 0.25 points to the final score. Next, the ratio of positive comments was calculated, and the resulting decimal was added to the score. Lastly, one point was added for proposed projects that were near schools and parks. Once final scores were tabulated, they were added into the proposed projects layer in ArcGIS Pro. A new field titled *CommEngage* was created and calculated using the following Arcade script:

$$
\begin{gathered}
var\ x\ =\ \$feature.Label \\
var\ CommEngage\ =\ When(x\ ==\ '121\ -\ Woodside\ Rd.', 2.17, \\
x\ ==\ '113\ -\ El\ Camino\ Real', 2.6, \\
x\ ==\ '60\ -\ Roosevelt\ Ave.', 2.25, \\
x\ ==\ '59\ -\ Redwood\ Ave.', 2.25, \\
x\ ==\ '64\ -\ Jefferson\ Ave.', 2.25, \\
x\ ==\ '73\ -\ Vera\ Ave.', 2.5, \\
x\ ==\ '74\ -\ Vera\ Ave.', 2.5, \\
x\ ==\ '17\ -\ Maple\ St.', 2, \\
x\ ==\ '20\ -\ Maple\ St.', 1, \\
x\ ==\ '122\ -\ Maple\ St.', 2, \\
x\ ==\ '82\ -\ Hudson\ St.', 2, \\
x\ ==\ '34\ -\ Alameda\ de\ las\ Pulgas', 2.25, \\
x\ ==\ '36\ -\ Alameda\ de\ las\ Pulgas', 1.75, \\
x\ ==\ '98\ -\ Alameda\ de\ las\ Pulgas', 1.25, \\
x\ ==\ '54\ -\ Madison\ Ave.', 1, \\
x\ ==\ '119\ -\ Arguello\ St.', 2, \\
x\ ==\ '12\ -\ Path\ through\ Red\ Morton\ Park', 2.25, \\
x\ ==\ '18\ -\ Path\ from\ Seaport\ Blvd.\ to\ Veterans\ Blvd.\ under\ U.S.\ 101', 1, \\
x\ ==\ '72\ -\ Poplar\ Ave.', 2, \\
x\ ==\ '75\ -\ Myrtle\ St.', 2, \\
x\ ==\ '37\ -\ Middlefield\ Rd.', 2.25, \\
x\ ==\ '49\ -\ Middlefield\ Rd.', 1.25, \\
x\ ==\ '111\ -\ Middlefield\ Rd.', 2.25, \\
x\ ==\ '120\ -\ Middlefield\ Rd.', 2.25, 0) \\
return\ CommEngage
\end{gathered}
\tag{13}
$$

where *x* is set equal to *$feature.Label* which represents the label attribute of the proposed project and *CommEngage* represents the community engagement score attribute. The script instructs

ArcGIS Pro to iterate over the features in the proposed project dataset and assigns values to the *CommEngage* attribute based on the value of the *Label* attribute.

Another post-workshop step was sending a follow up email to all participants. This email thanked them for their input and included a link for them to view the workshop recording at their leisure.

3.4 Equity Analysis

Because funding for infrastructure improvement projects is not infinite, it is important to strategically prioritize projects for actual implementation. Areas that have historically been underserved by infrastructure and educational opportunities and that have a relatively low median household income are often targeted for improvements by cities and developers in an effort to level the societal playing field. In some instances, infrastructure improvement projects undertaken in these areas may be eligible for external funding from private, regional, state, and/or federal sources.

After corresponding with Ms. Owrang, it was decided that the equity quantifications of four different organizations would be referred to when determining which proposed projects to prioritize based on their equity impact. Each of the organizations' websites identify areas within their respective jurisdictions that have been historically underserved, have a lower-than-average median household income, or have a significant minority population. The four organizations are listed below, along with maps of the areas in and around Redwood City that they deem as having previously been inequitably served by government programs.

The first organization was the City/County Association of Governments (C/CAG) of San Mateo County. C/CAG used a custom criterion which included three variables to determine where their equity focus areas were located. These criteria were median household income, race/ethnicity, and the housing and transportation affordability index. Figure 20 shows a map of the C/CAG equity focus areas in and around Redwood City. The data was acquired from the C/CAG online map (C/CAG of San Mateo County n.d.). While the data could not be directly downloaded, it is aggregated at the Census Block Group level. To visualize the C/CAG equity focus areas in ArcGIS Pro, corresponding block groups were selected from a Census Block Group layer and a new layer was created from the selection.

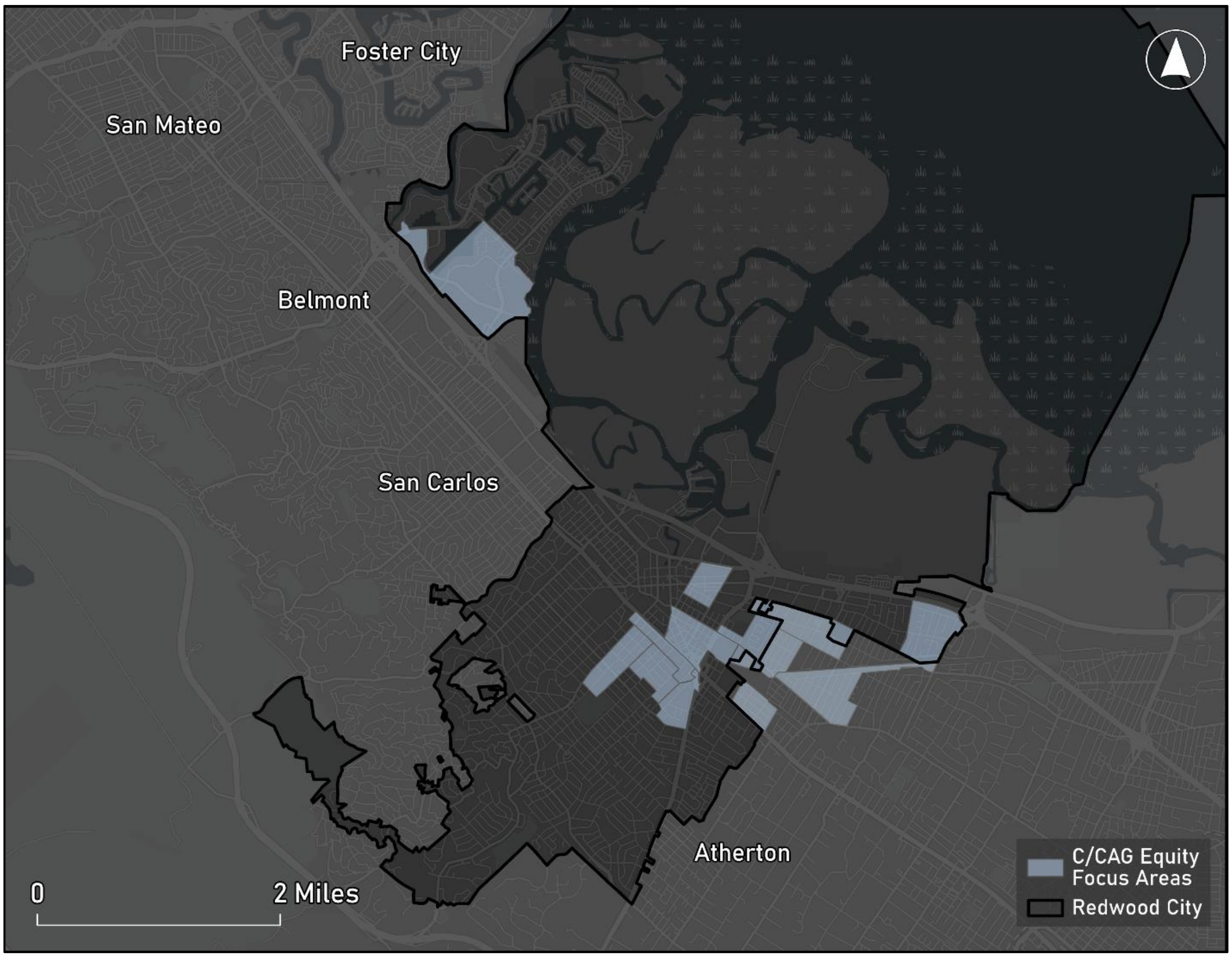


Figure 20. C/CAG Equity Focus Areas

The second organization was SamTrans, the transportation agency that runs bus services within San Mateo County. SamTrans has established their own set of priority areas that have historically been underserved by public transportation. SamTrans actively works to improve bus route connectivity in these areas. SamTrans determined their equity priority areas based on three criteria: median household income, the presence of racial and ethnic minorities, and the zero-car household rate. Figure 21 shows a map of the SamTrans equity focus areas in and around Redwood City. The data was acquired from ArcGIS Online (ShockleyD_Samtrans 2022). The link was provided by Ms. Owrang.

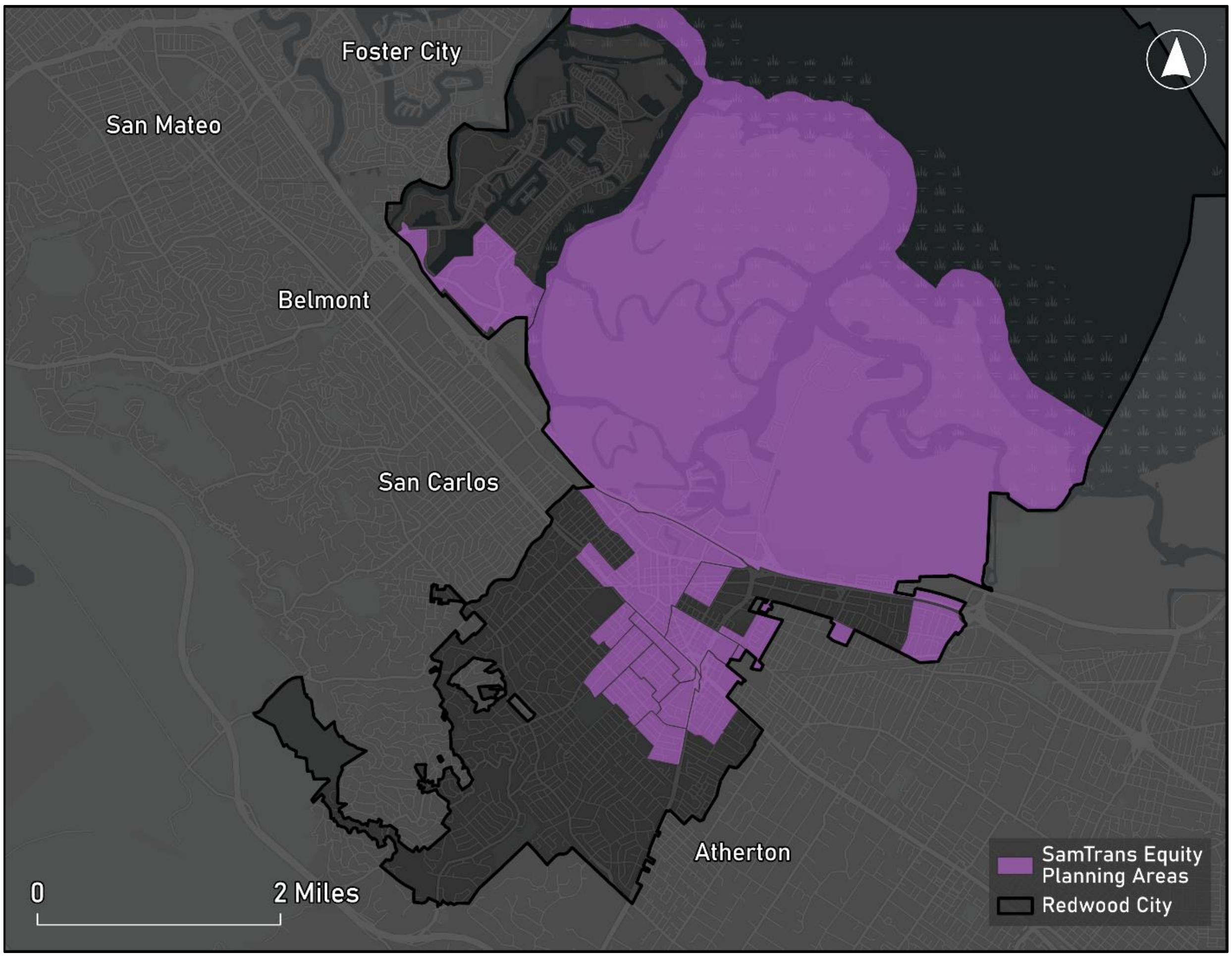


Figure 21. SamTrans Equity Planning Areas

The third organization was the Metropolitan Transportation Commission (MTC) which is the agency that oversees transportation across the nine counties that make up the San Francisco Bay Area. The MTC had identified census tracts within their jurisdiction that are considered equity priority communities (EPCs). EPCs were determined by looking at the following demographic criteria: people of color, low income, limited English proficiency, zero-vehicle households, seniors over 75 years old, people with disabilities, single-parent families, and rent burdened households. Projects within MTC EPCs are eligible for grants and are therefore more likely to be implemented as a result of available funding. Figure 22 shows a map of the MTC EPCs. The data was acquired from the MTC's open data portal website (MTC GIS 2022).

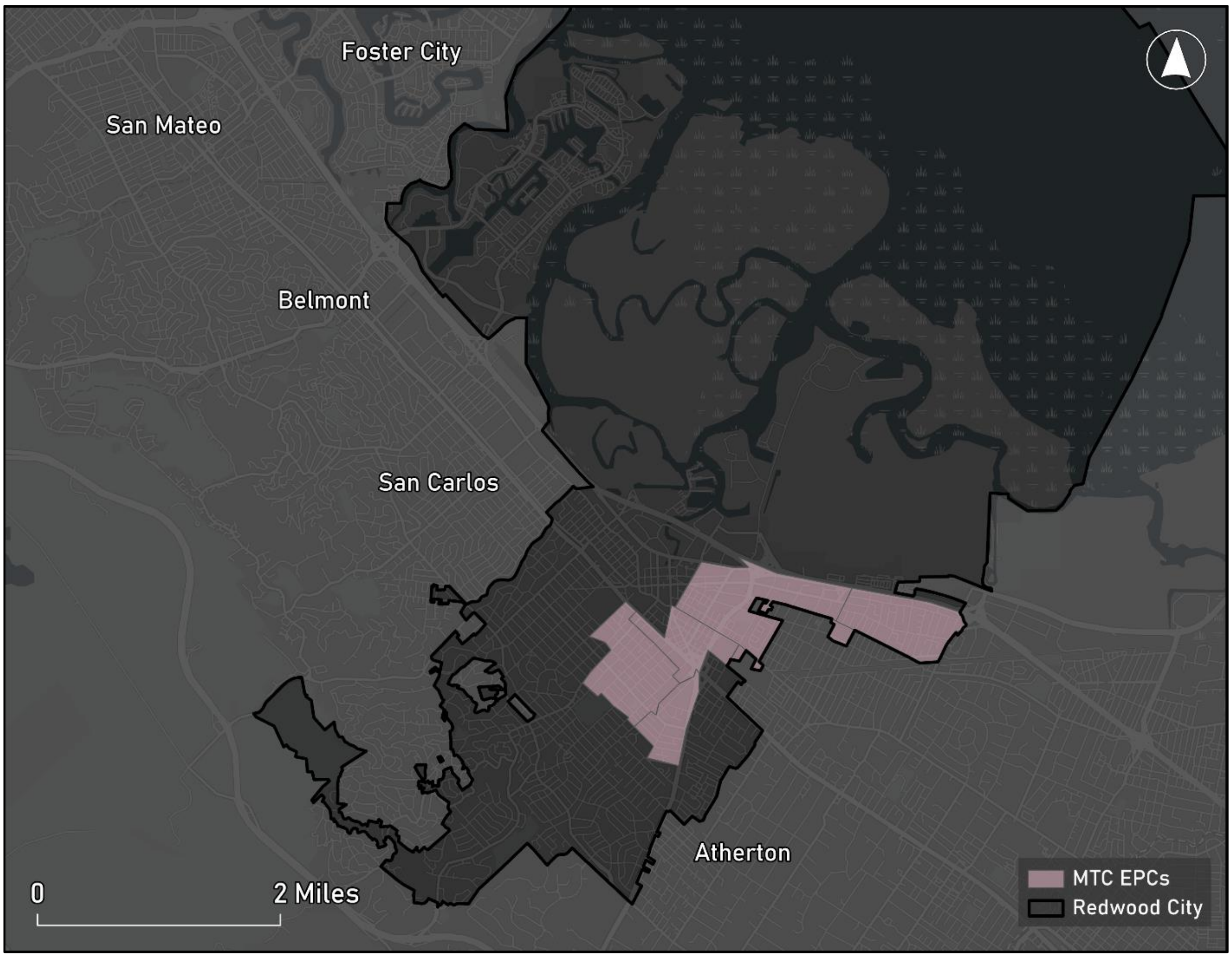


Figure 22. MTC EPCs

The fourth equity quantification was the California Healthy Places Index (CAHPI). The CAHPI dataset was created by the Public Health Alliance of Southern California and assigns neighborhoods across California with a score that quantifies the relative health of a community based on 25 factors, including healthcare access, housing availability, and education quality. While the CAHPI is not a direct stakeholder, rather it is a data-derived index, Ms. Owrang recommended it be used to assess the equity impact of the proposed projects. Redwood City communities below the 50th percentile across the state were selected as being relevant to the equity analysis. Figure 23 shows a map of the neighborhoods in and around Redwood City that scored beneath the 50th percentile in the CAHPI. The data was available on the CAHPI website (Public Health Alliance of Southern California n.d.). While the data could not be directly downloaded, it is aggregated at the Census Tract level. To visualize the CAHPI Census Tracts in the bottom 50th percentile in ArcGIS Pro, corresponding tracts were selected from a Census Tract layer and a new layer was created from the selection.

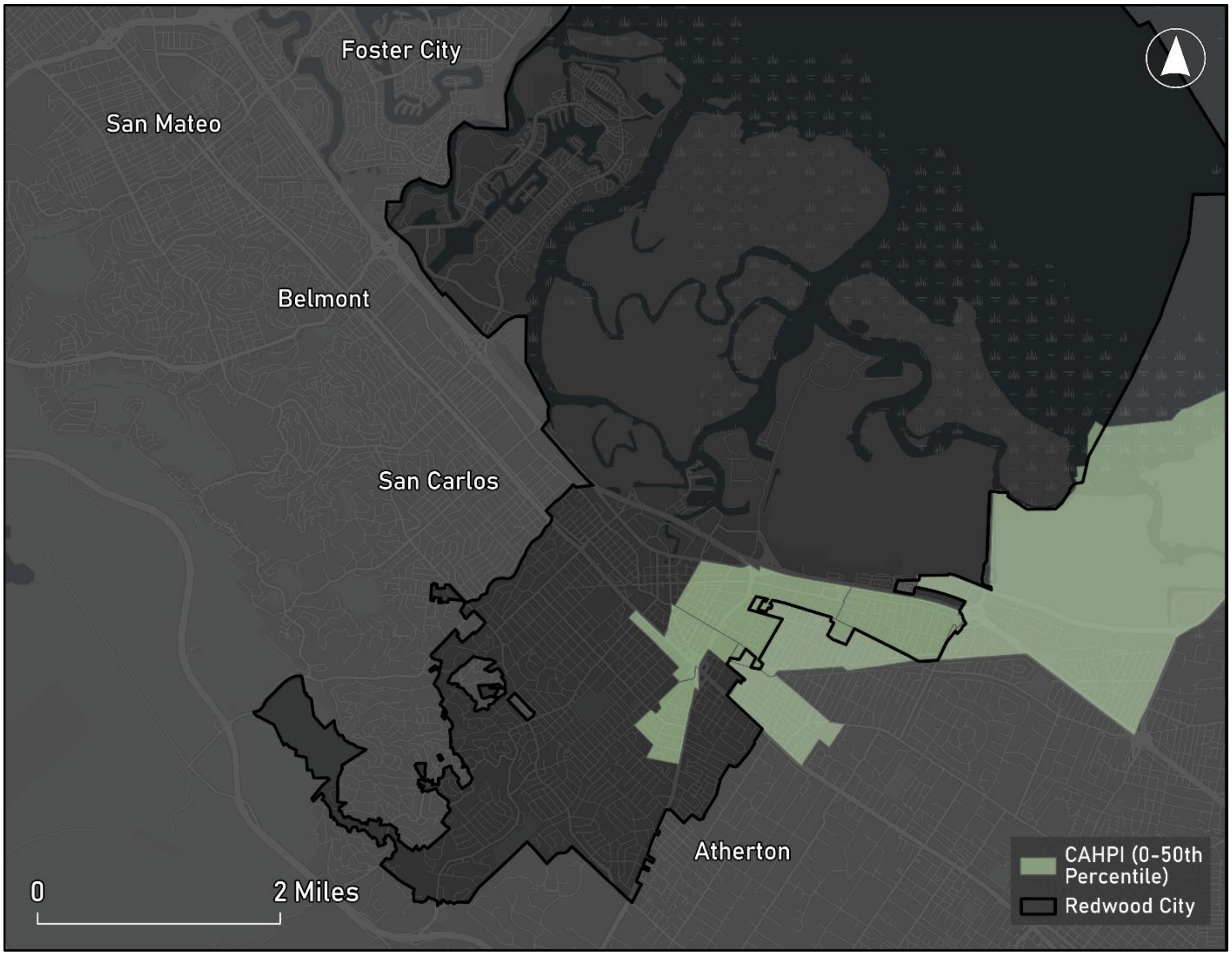


Figure 23. CAHPI polygons

Four new fields were added to the 132 proposed projects' attribute table, and each field was named for one of the four equity polygon datasets. A *ModelBuilder* was developed to assign each proposed project a value for each of the four attributes (Figure 24). The model used the *Select Layer by Location* tool to select proposed projects that overlapped each respective equity polygon dataset. The selected proposed projects were then used as the input for the *Calculate Field* tool. This tool used a short Python script to assign a binary attribute value for each proposed project. If a proposed project overlapped an equity polygon, the attribute was assigned a value of one. If a proposed project did not overlap an equity polygon, the attribute was assigned a value of zero.

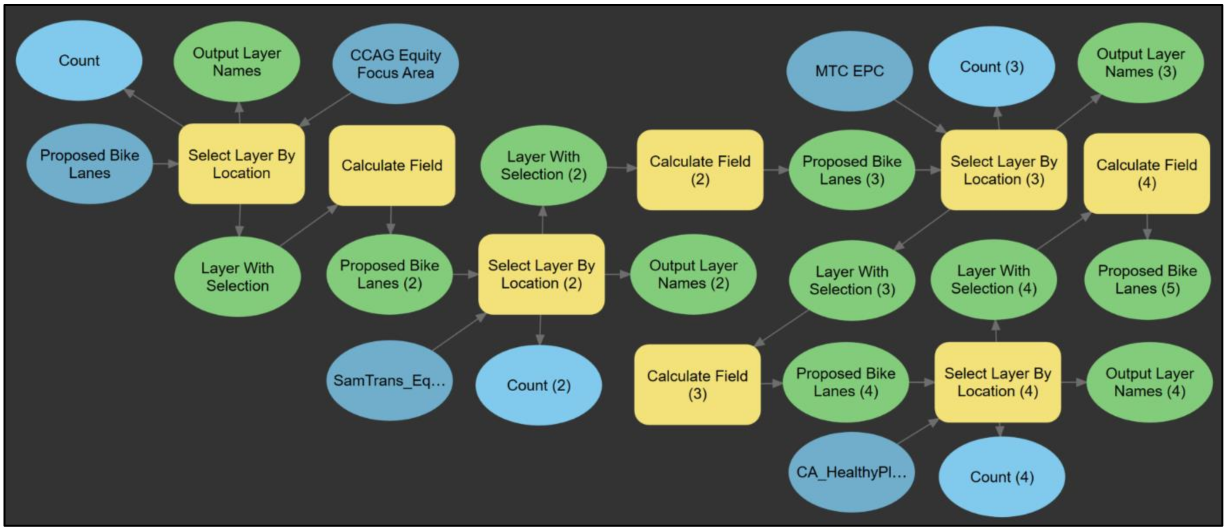


Figure 24. Equity score *ModelBuilder* layout

Next, an additional field was created and titled *EquitySum*. Because there were four sets of equity polygons, the maximum value for this field was four (if a proposed project overlapped all four equity polygons) and the minimum value for this field was zero (if a proposed project overlapped none of the four equity polygons). This attribute was calculated by summing the binary scores assigned to each individual equity attribute calculated in the *ModelBuilder*. This was done by using the following Arcade script within the *Calculate Field* tool:

$$\begin{gathered} var\ EquitySum = (\$feature.SamTrans \\ + \$feature.MTAEPC \\ + \$feature.CAHPI \\ + \$feature.CCAG\_EFA) \\ return\ EquitySum \end{gathered} \tag{14}$$

where *EquitySum* refers to the total equity score of the proposed project, *$feature.SamTrans* refers to the SamTrans attribute value of the proposed project feature layer, *$feature.MTCEPCs* refers to the MTC EPC attribute value of the proposed project feature layer, *$feature.CAHPI* refers to the CAHPI attribute value of the proposed project feature layer, and

$feature.CCAG_EFAs refers to the CCAG Equity Focus Areas attribute value of the proposed project feature layer.

3.5 Site Selection

This section discusses the methodology applied to prioritize proposed projects and determine which three would move on to the design stage of the project. This was done by using a weighted sum equation to compute each proposed project's prioritization score based on its level of bikeability, equity impact, and the extent, if any, it received public support during the workshop.

The final step in calculating the site selection rankings was to perform a weighted sum combining the proposed project's ability to improve equity, bikeability, and meet public needs. Each of the three inputs was assigned a nearly identical weight, with equity being weighted 33%, bikeability 33%, and public needs 34%. These weights were selected as each of the three input variables are of relative equal importance. This would also help break ties in the event of multiple proposed projects scoring the same for a given variable. A new field titled *EqBikePe* was added and calculated using the following Arcade script:

$$\begin{gathered} var\ x\ =\ (\$feature.EquitySum\ *\ .33) \\ +\ (\$feature.BikeReclass\ *\ .33) \\ +\ (\$feature.CommEngage\ *.34) \\ return\ x \end{gathered} \tag{15}$$

where *x* represents the priority score of a proposed project, *$feature.EquitySum* represents the equity score of a proposed project, *$feature.BikeReclass* represents the bikeability score of a proposed project, and *$feature.CommEngage* represents the workshop score of a proposed project. The numeric values which are used to multiply each respective attribute represent the overall weight of the associated attribute as it pertains to evaluating bikeability.

Once calculated, the *EqBikePe* attribute could be sorted in descending order in ArcGIS Pro to identify which projects scored the highest. A map indicating the priority score of each proposed project was also created.

3.6 Proposed Project Design Concepts

Diagrams and models of infrastructure proposals were created for the three highest-scoring projects that did not already undergo a city design process. The development of final design proposals is linear and was repeated for each of the three projects. Google Maps and spatial data were used to investigate the surrounding contexts of each site, with the investigation results influencing the final design concept. SketchUp was used to create the final designs. All designs include fully protected Class I bike lanes, as workshop participants were adamant that these should be strongly prioritized over other class options.

3.6.1 Site Investigation

The physical and social characteristics of the area surrounding each selected project were investigated in order to become familiar with the site context. This was done to allow each project to be optimized for its particular location within Redwood City.

3.6.1.1 Current status assessment

While "walking" down the street using Street View in Google Maps, specific observations regarding the size of the street, the presence of sidewalk buffers, and the type of housing were documented. The purpose of this step was to become familiar with the site and how someone interacting with it may view it. The author was also able to apply their own experience of living in Redwood City and was able to assess how busy the street may be at any given time, and whether it should be considered an arterial transit corridor or a street for local traffic. This is important to know because if the road is not heavily trafficked, and there are parallel alternatives near it, it is possible to consider a road diet. A road diet refers to downsizing the number of lanes on a road in favor of bike or pedestrian infrastructure or the implementation of one-way traffic. Screenshots were taken of the Google Street View imagery for each site and were referenced during the design process.

Another important task to undertake during the status assessment was to locate nearby schools, parks, retail, and mixed-use facilities. These places serve as key destinations for cyclists and their location can alter the orientation of the new bike infrastructure design. For example, if there is a park and retail center on the north side of one of the streets under investigation, it may be better to have a two-way bike lane on the north side of the street, rather than have one-way bike lanes on either side of the street. Looking at existing bike infrastructure is also important, especially if it intersects with the street under investigation, as this can influence the orientation of the new design. Lastly, it is important to locate existing driveways, as in the new designs, space will need to be left for cars to enter off-street properties. A map was created in ArcGIS Pro to visualize nearby schools, parks, mixed-use, retail, and existing bike lane facilities making use of data downloaded from the San Mateo County and Redwood City GIS data portals and was referenced during the modeling process.

3.6.1.2 Demographics of the surrounding neighborhood

The demographic investigation focused on the percentage of households that did not own a car. This is a key metric, because if this number is high, that implies less parking is needed and the decision to either maintain the existing parking situation or remove parts of it in favor of added bike or pedestrian infrastructure can be made. Median household income and non-white percentage were two other demographics that were investigated. This information was documented and referred to during the design modeling phase of the thesis.

3.6.1.3 Zoning designations of the surrounding neighborhood

If there are a lot of single-family parcels, street parking may be more necessary due to limited garage sizes and the fact that many families own multiple cars. However, if there are a lot of multi-family parcels, there may be fewer cars on the street due to the existence of apartment complex garages. Furthermore, dense housing near frequent and reliable transit options may require less parking as residents could be more inclined to use bikes, SamTrans, or CalTrain as a primary form of transit. A map of the zoning designations for the parcels surrounding the proposed project was created in ArcGIS Pro using the original zone data file that was downloaded from Redwood City's GIS data portal (Redwood City GIS n.d.) and was used to inform the modeling process.

3.6.2 Modeling

StreetMix is an online application that allows users to design street cross-sections by dragging and dropping various street infrastructure components on an online canvas (StreetMix n.d.). StreetMix was used to create an illustration of the potential cross-section of the newly designed street. The width of the street was determined by measuring the distance between property lines across the street in Google Maps. The StreetMix street interface was then set to the same distance and components such as driving lanes, parking lanes, bike lanes, sidewalks, and sidewalk buffers were dragged on until the space was filled. The width of each component could be adjusted depending on size constraints; however, each component was restricted by a minimum width as determined by StreetMix restrictions as well as local planning regulations. Once a satisfactory design had been created, a screenshot of the interface was taken.

In ArcGIS Pro, the street containing the proposed project of interest was selected from the polyline layer featuring all of Redwood City's streets. A new layer was created from the selection, isolating the proposed project-of-interest street line. The line was then exported as a .dwg computer-aided design (CAD) file and stored on the desktop.

A new Sketchup Pro file was created. The .dwg file containing the linework of the proposed project street was imported into the file. The entirety of the line was selected and the *Weld Edges* tool was applied, which merged each of the individual street segments into one continuous line geometry.

The SketchUp to OpenStreetMap (skp2osm) plugin was then downloaded from the OpenStreetMap (OSM) Wiki. This plugin is compatible with SketchUp and allows the user to add geometry from OSM directly into a SketchUp file.

Next, OSM was accessed through an internet browser window. The street segment of interest was centered on the map page. The export button was selected (Figure 25, upper left), followed by the "manually select a different area" option (Figure 25, upper right). A rectangle appeared on the page and the author centered it around the road of interest, ensuring that adjacent buildings, intersections, and roads were all within the rectangle frame. The export button was then clicked and an .osm file was downloaded, containing all building footprint and road geometry (Figure 25, bottom).

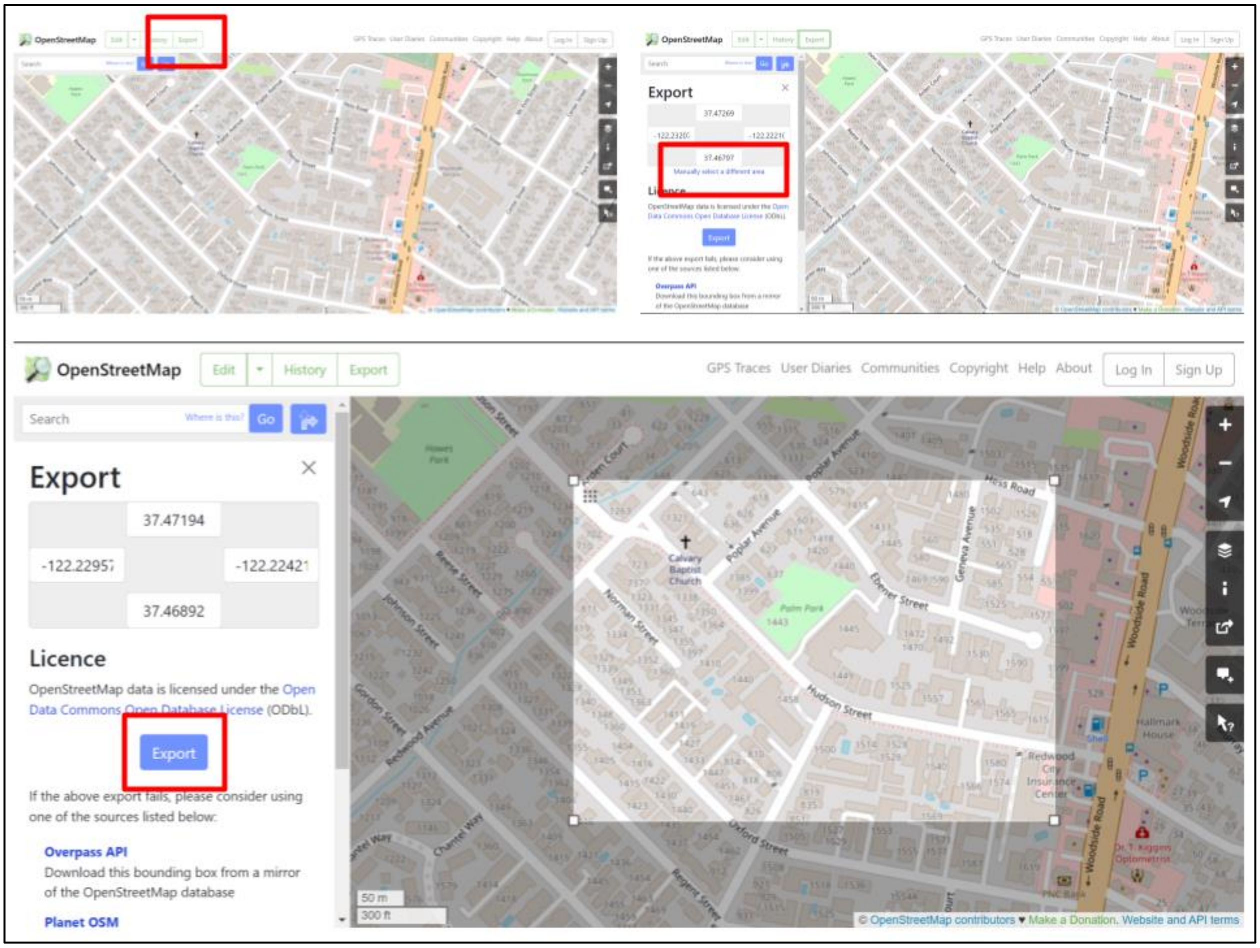


Figure 25. OSM data download steps

Back in the SketchUp file, the .osm file containing the building footprint and road geometry was imported. The road geometry representing the road of interest was then deleted. The line previously created by merging the street segments was then selected and moved into the correct geographic location within the matrix of OSM buildings. Because the OSM selector tool is a rectangle that is centered on the road of interest, there are building footprints and streets present in the OSM file that are irrelevant to the study area. These irrelevant features serve no purpose and only slow down SketchUp processing speeds. The unneeded features were selected and deleted from the project file.

Next, the remaining buildings which are relevant to the proposed project, meaning they are either adjacent or otherwise close to the street, were given a 3D appearance. This was done by manually applying the *Extrude* tool to each building footprint and dragging the footprint upwards to a certain height. The height was estimated by using Google Street View and Google Maps in a 3D view.

Next, a cross section of the proposed project was created perpendicular to the end of the street linework. The cross section of the proposed infrastructure was centered on the endpoint of the street linework. The cross section must be two-dimensional and cannot be represented by a line, so it was created one foot deep. Lines were created perpendicular to the cross section and were located based on the proposed street design. A line parallel to the initial cross section line was created one foot back, resulting in rectangular areas that represent the various sections of the street (sidewalk, sidewalk buffer, bike lane, bike lane buffer, parking lane, road lane, etc.).

Each rectangular area was then assigned a material. Sidewalks and bike lane curb barriers were assigned concrete material. The road and street parking rectangles were assigned asphalt material. The sidewalk barriers were assigned grass material. The bike lanes were assigned a green material that was similar in color to the green paint already used by Redwood City to mark bike lanes.

By this time, a cross section of the proposed street design had been created. It was one foot long and as wide as the street (for example, 18m) and split up into rectangular sections, each indicating a different use of the right of way. Lastly, each rectangular section was extruded one foot downwards, ensuring that a 3D geometry was created with the top maintaining the same elevation as the road linework and the bottoms of the buildings.

Next, the *Follow Me* tool was used to stretch the cross section along the length of the street line. Each face of each 3D section (sidewalk, sidewalk buffer, bike lane, etc.) had to be created individually using the *Follow Me* tool. First, the *Follow Me* tool was selected from the SketchUp toolbar. Next, the line representing the street was selected. Next, the face of the 3D road segment was selected. The end of the street line was then selected, and the 3D road segment followed the linework to the opposite end. This was repeated for each 3D component making up the proposed design. By the end of this process, the proposed design had been stretched to match the length of the street segment while also maintaining any curves in the street segment line shape.

Next, each design was customized to fit in with the surrounding built context. The first step of customizing the street design with the existing surrounding context was adding cross-streets and creating intersections. This was done using the spaces left behind by roads that were found in the original OSM map. The center point of the off-shooting road was determined and its location along the newly designed road was clicked. A line was created between this point along the edge of the newly designed road and the end of the intersecting road. This line was nine meters long, as it was meant to be half of the intersecting road width, which was in all cases 18m wide. This was repeated in the other direction. Once the overall space of the intersecting road was created, sidewalks and the street could be created using the *Line* and *Material* tools. Next, all sidewalks, sidewalk buffers, and bike lane curbs were extruded six inches upwards, matching the height of an average curb and resulting in a three-dimensional model.

Various features had to be customized for each site. Using the *Line* tool in SketchUp driveways that connected to the street, cutting through bike lanes, were drawn out and assigned the concrete material. The same was done for walkways that led from the sidewalk to the building entrances. 3D tree models were also imported from the SketchUp 3D warehouse and placed on both private properties as well as the sidewalk medians. Bike lane stencils were added to the bike lanes. White squares were also added to the bike lanes at instances where they were intersected by roads or driveways. The addition of these squares was meant to increase bike lane visibility and were inspired by similar techniques used in The Netherlands (Figure 26). Additionally, speed limit signs, stop signs, crosswalk signs, and one-way signs from the SketchUp 3D warehouse were added as needed.

Figure 26. Netherlands bike lane driveway infrastructure

Once the design was complete, the SketchUp view was changed from a parallel projection to a perspective view. This allowed the *Position Camera* and *Look Around* tools to be used to position the model in a manner that would be suitable for final rendering. For each model, one view was created from the perspective of a cyclist or pedestrian and one view was created from an aerial perspective.

V-Ray for SketchUp was downloaded from Chaos and was used to create site renderings. V-Ray works well with SketchUp and was first installed and added as an extension. It was then opened, and the settings were adjusted to produce a quality rendering. The lighting setting was set to dome light, and a sky-blue image was used to provide background coloring. In the general V-Ray settings, progressive render was turned off, the quality was set to high, the denoiser was toggled on, the image width was set to 1,920 pixels, image height was set to 1,080 pixels, and a file path was created to automatically save the output rendering as a .png file. V-Ray was then run, and renderings were produced. Based on the rendering results, the author could choose to adjust the camera angle and re-run V-Ray.

Following the design modeling process, six deliverables were created for each of the three selected proposed projects: an imagery map of the area around the proposed project, an amenity map of the area around the proposed project, a zoning map of the area around the proposed project, a StreetMix diagram, and two renderings of the new design.

Chapter 4 Results

The objective of the work described in this thesis was to provide conclusions for advancing Redwood City's bicycle infrastructure based on a geodesign workflow. The approach was built around five research elements: (1) quantification of Redwood City's bikeability as of 2022; (2) solicitation of input from local residents on the current (2023) and proposed cycling infrastructure of Redwood City; (3) evaluation of Redwood City's proposed cycling infrastructure projects to positively impact issues of economic, social, and transit inequality; (4) selection of three proposed cycling infrastructure improvement projects that should be most prioritized; (5) conceptual designs for potential projects that were assessed to be of potential highest impact.

4.1 Bikeability Quantification

The result of the bikeability assessment for Redwood City including the Redwood Shores area is depicted in Figure 27. The assessment is the combined output from the analysis of the posted speed limit, zoning designation, terrain, tree canopy, bike lane access and historic cyclist-involved accident data. Sections 4.1.1 and 4.1.2 describe the results for Redwood City and Redwood Shores respectively.

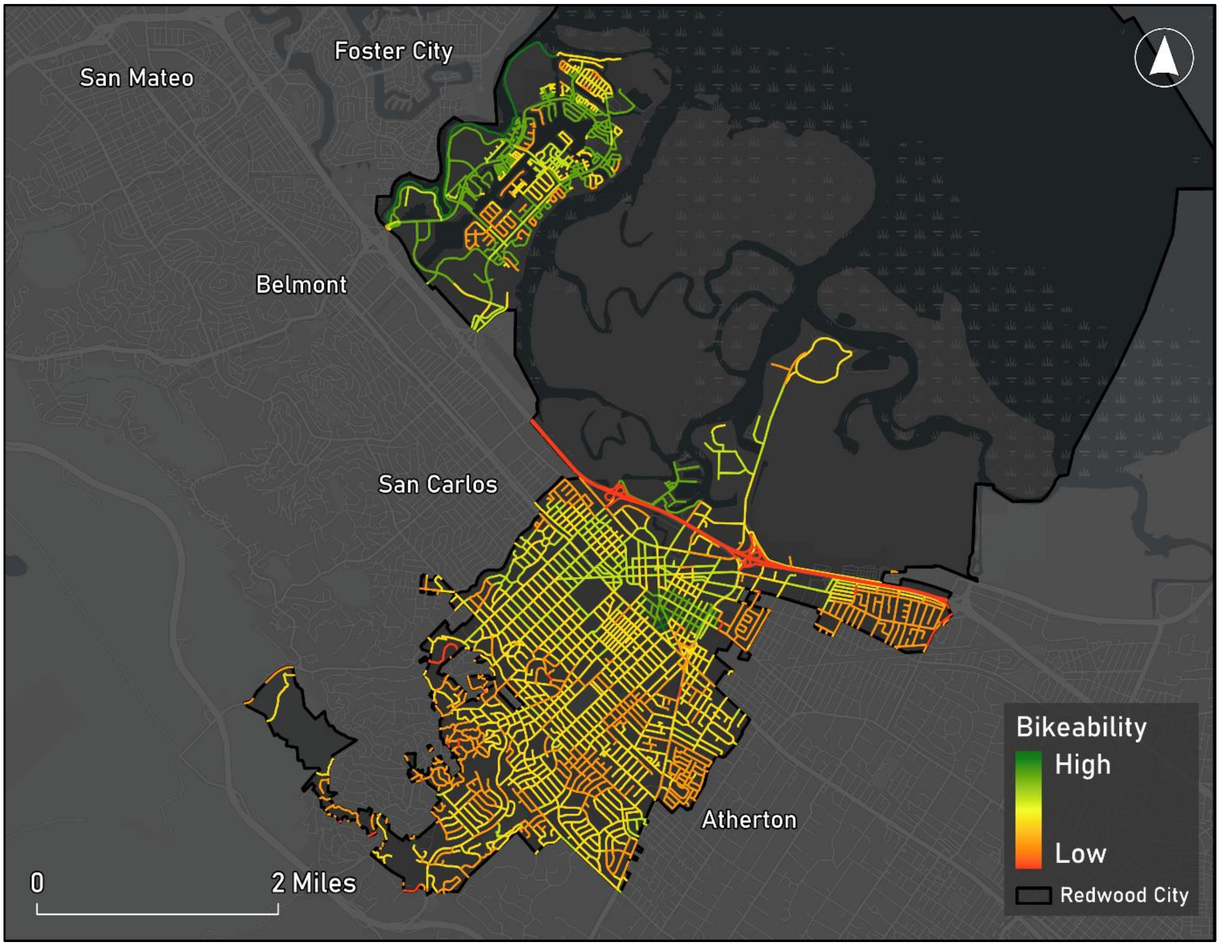


Figure 27. Redwood City bikeability

4.1.1 Redwood City Bikeability

In Redwood City, bikeability is overwhelmingly moderate, leaning towards the lower end of the bikeability spectrum (Figure 28). However, there are clusters of high bikeability within the city.

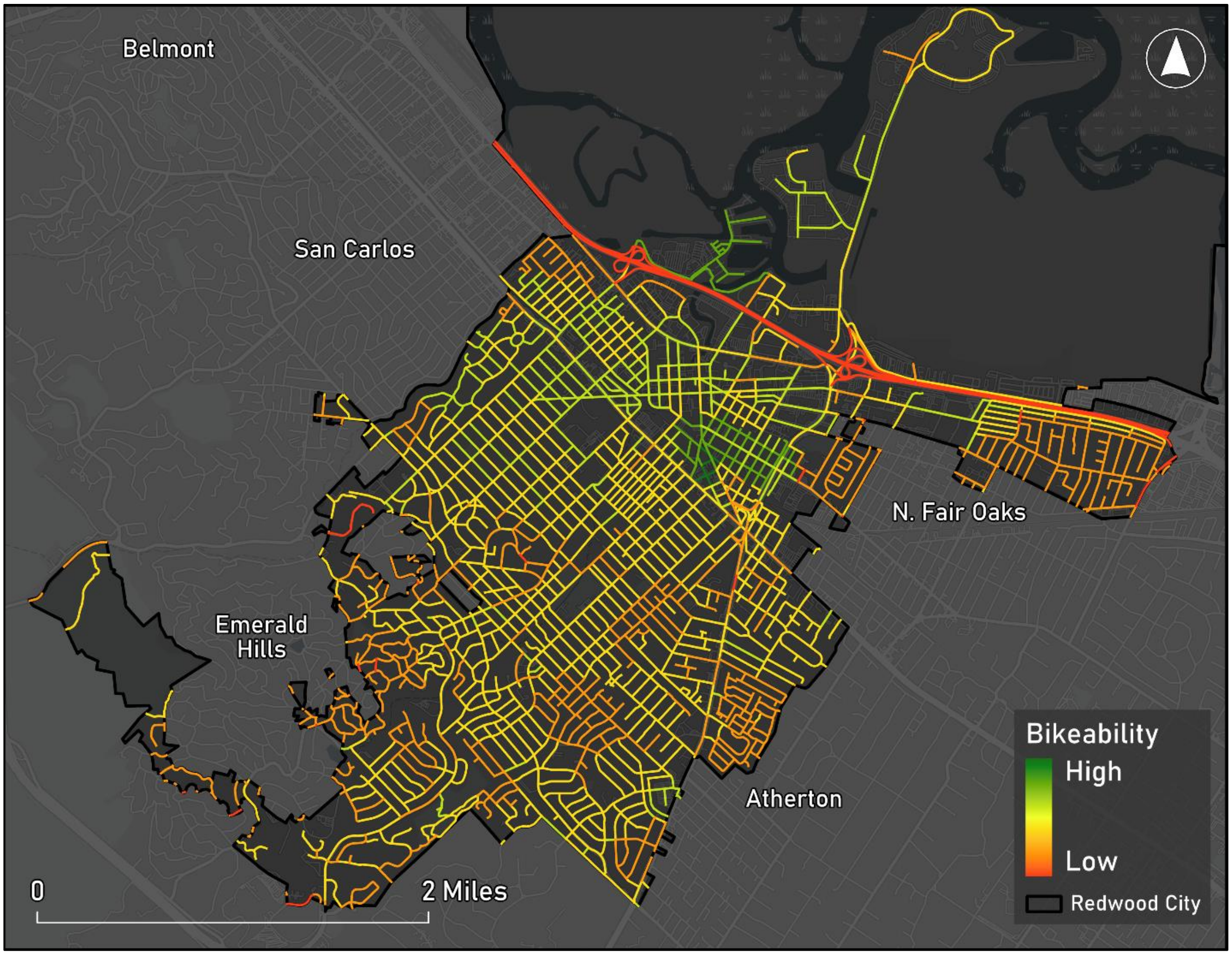


Figure 28. Redwood City bikeability (excluding Redwood Shores)

There are a few instances of high bikeability in Redwood City, mainly concentrated around the downtown area in neighborhoods 12, 13 and 14 (see Figure 29). Neighborhoods nine, 10, and 11 are residential, however they support moderate to high bikeability (see Figure 29). Neighborhoods one, two, three, four, five, six, seven, eight, 15, and 16 support low to moderate bikeability (see Figure 29). These neighborhoods are almost entirely residential, leaving a significant amount of the population with no access to bikeable infrastructure. This indicates that there is significant opportunity for improvement to Redwood City's cycling network.

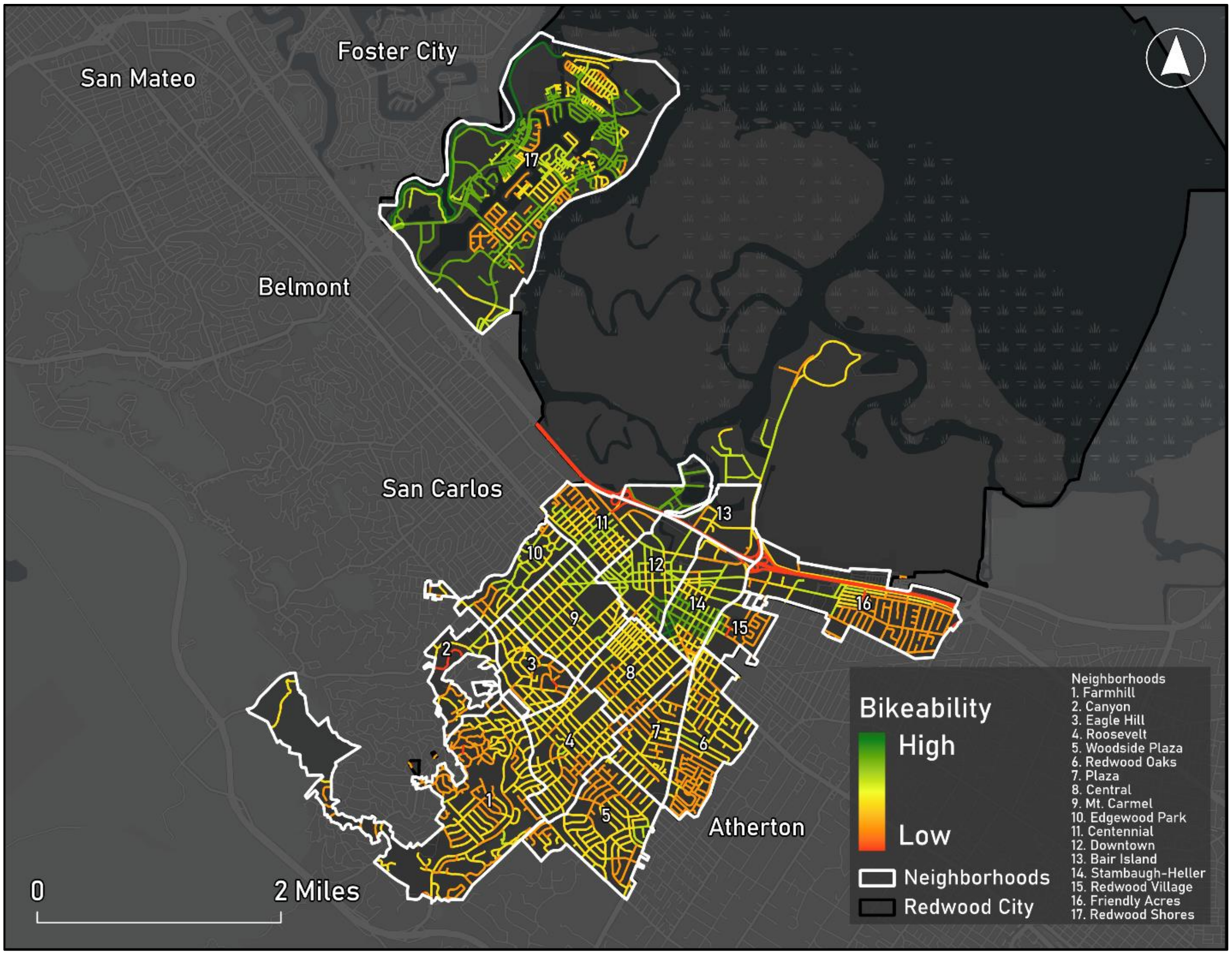


Figure 29. Redwood City bikeability and neighborhoods

4.1.2 Redwood Shores Bikeability

In Redwood Shores, bikeability is generally high (Figure 30). While there are a few instances of low bikeability, these street segments are found within quiet suburban areas and are not a major roadblock to cyclists. Redwood Shores is flat and was master planned with the inclusion of circumferential bike lanes that allow for straightforward travel throughout the surrounding area, fully separated from automobile roads. This makes it easy for residents to travel within Redwood Shores and comfortably ride from their homes to other homes, offices, or retail centers. The street segments scoring between low and moderate bikeability are generally restricted to single family residential areas where traffic is relatively slow. Despite the generally high bikeability, the bike infrastructure connecting Redwood Shores with the Bay Trail which leads into the main Redwood City area is not very developed and suggests that the bikeability between Redwood Shores and the rest of Redwood City is poor. Overall, Redwood Shores demonstrates high bikeability and can serve as an inspiration for future urban developments.

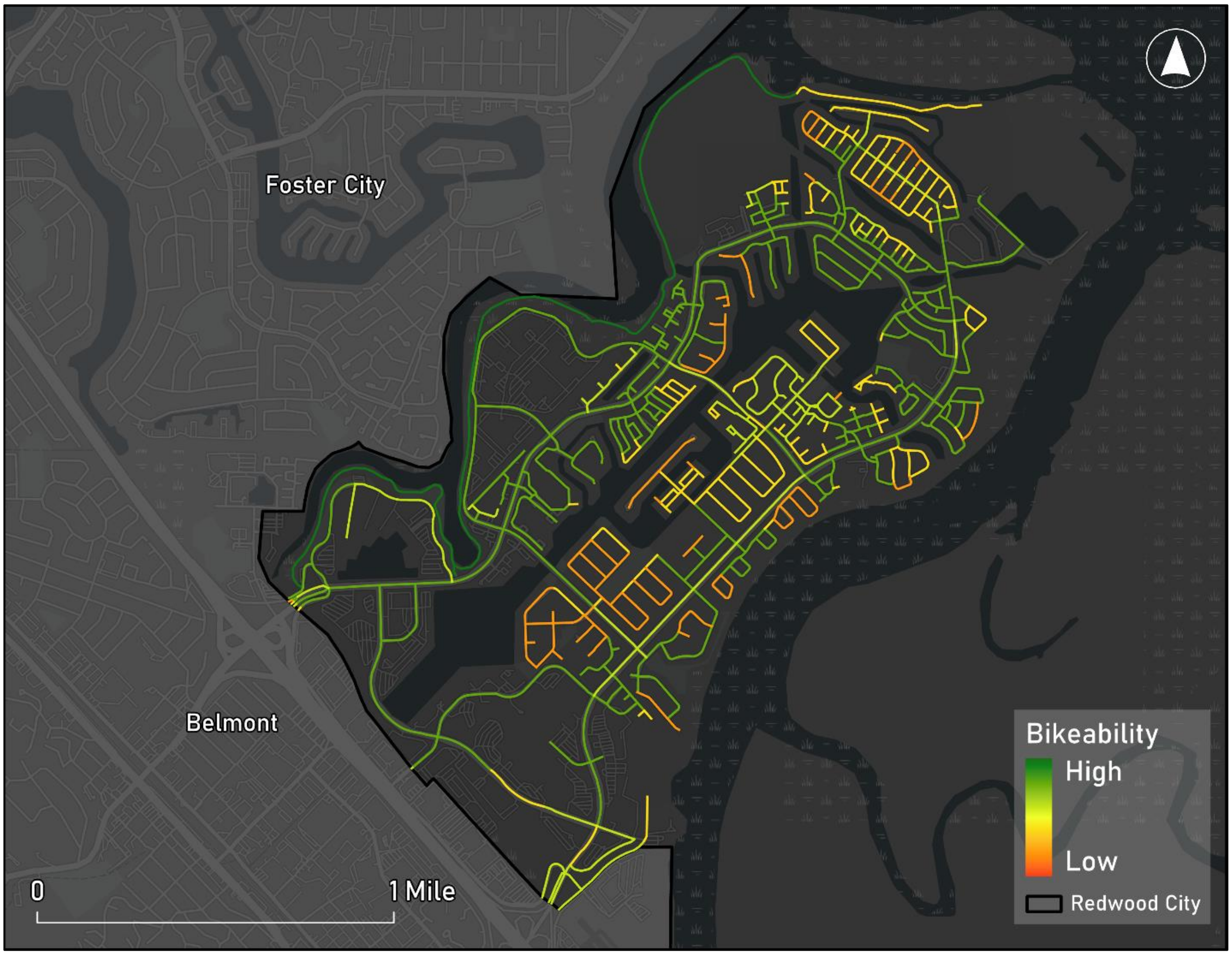


Figure 30. Redwood Shores bikeability

4.1.3 Proposed Projects' Bikeability

Bikeability was one of three input variables used to determine which proposed projects would be selected to receive design proposals, with the other two being workshop results and equity impact. The relative bikeability of each proposed project as of 2023 was determined using a methodology outlined in section 3.2.3. The results of the analysis are shown in Figure 31. Proposed project bikeability.

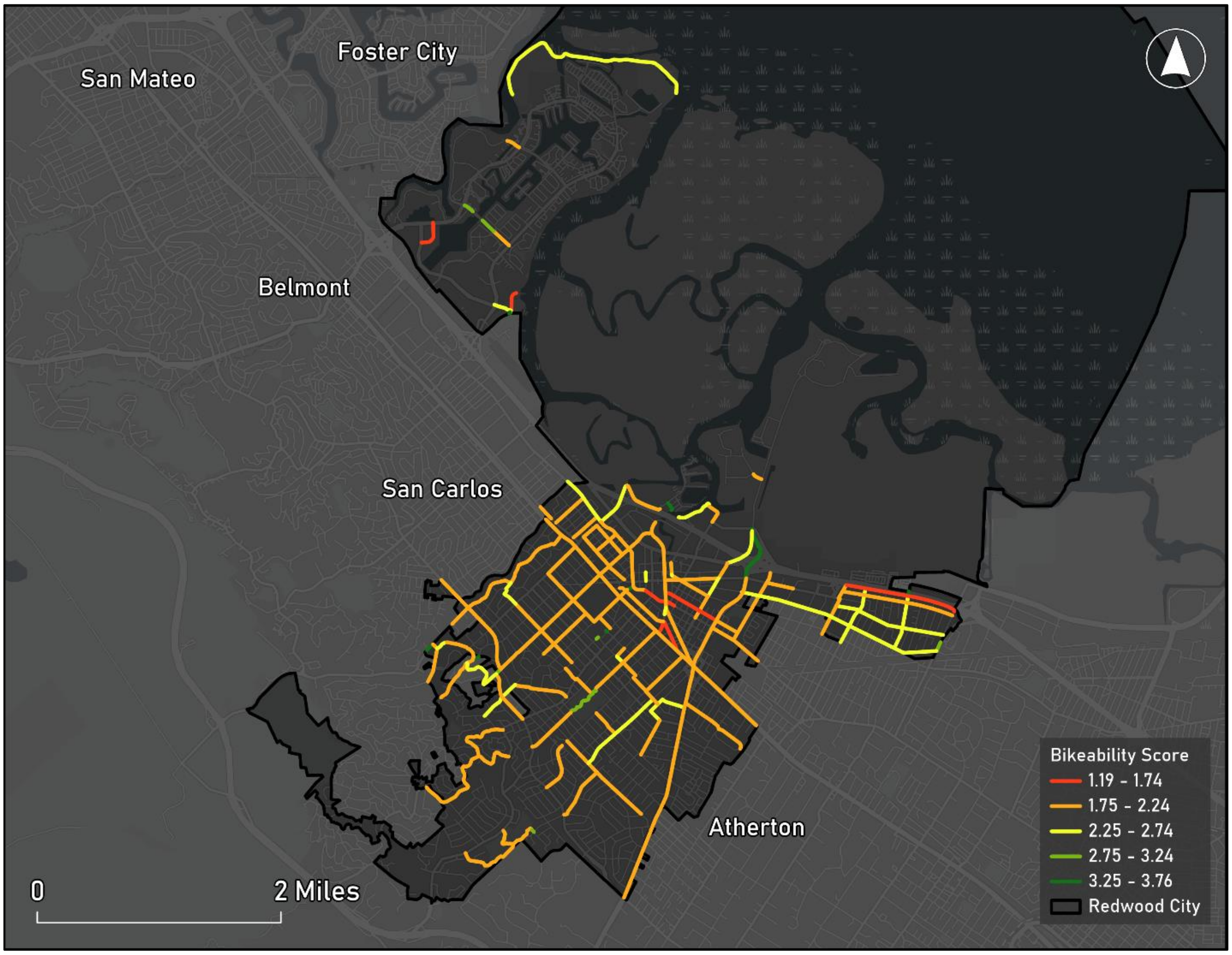


Figure 31. Proposed project bikeability scores

4.2 Workshop Findings

The workshop was structured to allow participants to give their input on the current (2023) and future state of bikeability in Redwood City through various communicative methods. Eleven total participants attended the workshop, with nine of them staying for the entirety of the event. The nine Redwood City residents that attended the whole workshop all participated in the interactive activities described below.

The different media for data collection, the Google Survey, Miro board activities, and verbal discussion sessions, resulted in similar outputs. Participants mentioned several streets and proposed projects where they would like to see better cycling infrastructure. After reviewing the survey results, Miro board, and workshop recording, a list of streets that received mentions was created along with the number of mentions and the number of proposed projects associated with each street. A map of the mentioned and associated proposed projects was also created (Figure 32).

Figure 32. Proposed projects mentioned in the workshop

Workshop participants also emphasized their interest in new cycling infrastructure being prioritized near parks and schools to create a safer rider environment for young bikers. As part of the quantification of workshop comments, a map was created to visualize the locations of parks and schools in Redwood City. A 500ft buffer was also added to identify specific parts of the city that should be targeted with improved infrastructure (Figure 33).

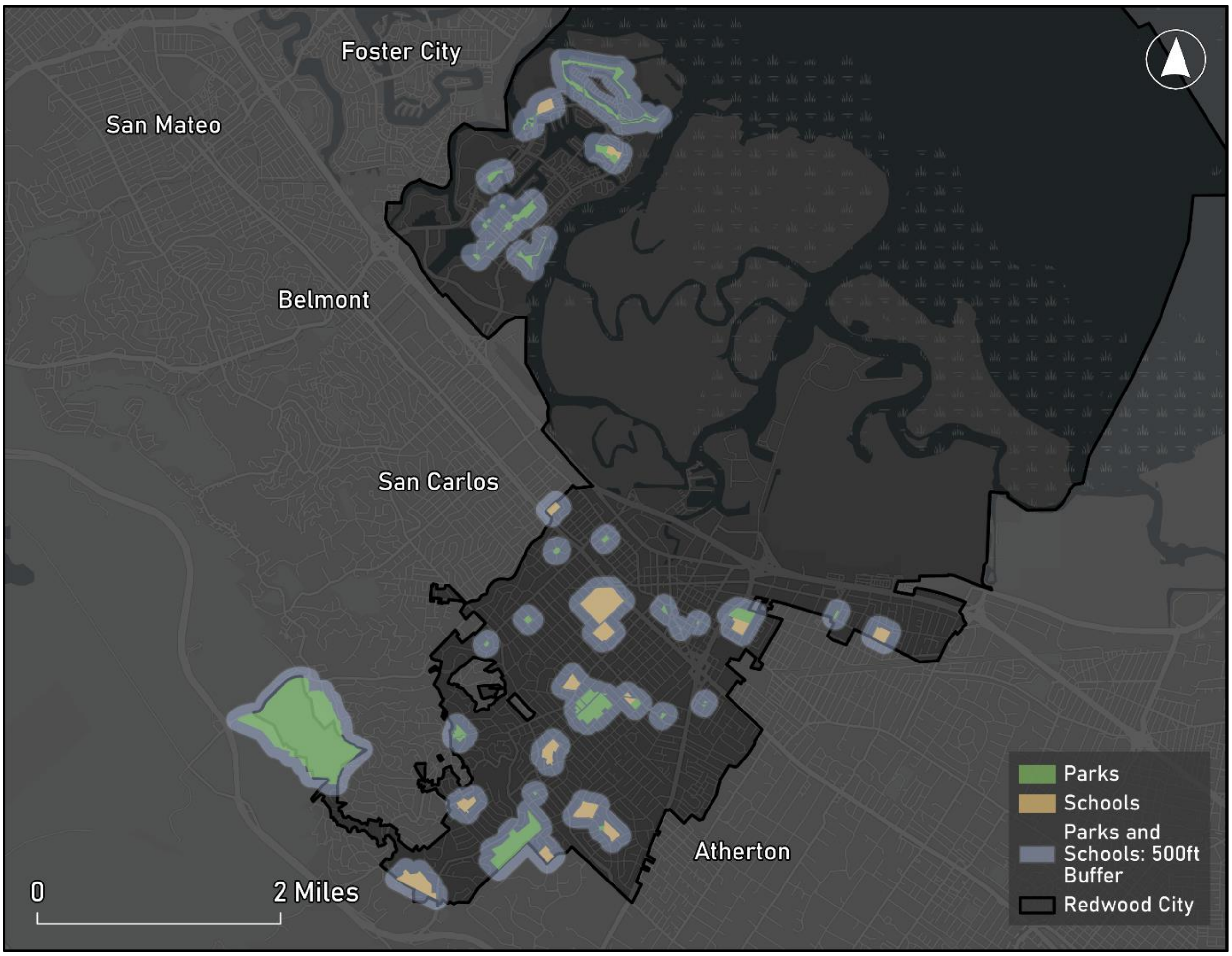


Figure 33. 500ft buffer around parks and schools

Using the list of mentioned streets, it was possible to extract the proposed projects associated with each street. In some cases, there was only one proposed project for a given street but in other cases, there were multiple proposed projects along a given street. A table of all 24 proposed projects that were either directly (mentioned in activity 3) or indirectly (associated with a mentioned street) mentioned during the workshop was created. The table included the proposed project number and name, the number of mentions, the number of positive mentions, the percentage of positive mentions, a binary value that indicates whether the project was within 500 feet of a school or park (yes is equal to one and no is equal to zero), and a final public feedback score. Final public feedback scores are listed in Table 12 for each proposed project that was mentioned during the workshop.

Table 12. Public feedback scores for proposed projects

Proposed Project ID Number and Name	Mentions	Positive Mentions	Mention Score	Percent Positive Mentions Score	Near School/Park Score	Public Feedback Score
34 - Alameda de las Pulgas	2	2	0.25	1	1	2.25
36 - Alameda de las Pulgas	3	3	0.75	1	0	1.75
98 - Alameda de las Pulgas	2	2	0.25	1	0	1.25
119 - Arguello St.	1	1	0	1	1	2
113 - El Camino Real	5	3	1	0.6	1	2.6
82 - Hudson St.	1	1	0	1	1	2
64 - Jefferson Ave.	2	2	0.25	1	1	2.25
54 - Madison Ave.	1	1	0	1	0	1
17 - Maple St.	1	1	0	1	1	2
20 - Maple St.	1	1	0	1	0	1
122 - Maple St.	1	1	0	1	1	2
37 - Middlefield Rd.	2	2	0.25	1	1	2.25
49 - Middlefield Rd.	2	2	0.25	1	0	1.25
111 - Middlefield Rd.	2	2	0.25	1	1	2.25
120 - Middlefield Rd.	2	2	0.25	1	1	2.25
75 - Myrtle St.	1	1	0	1	1	2
18 - Path from Seaport Blvd. to Veterans Blvd. under U.S. 101	1	1	0	1	0	1
12 - Path through Red Morton Park	2	2	0.25	1	1	2.25
72 - Poplar Ave.	1	1	0	1	1	2
59 - Redwood Ave.	2	2	0.25	1	1	2.25
60 - Roosevelt Ave.	2	2	0.25	1	1	2.25
73 - Vera Ave.	3	3	0.5	1	1	2.5
74 - Vera Ave.	3	3	0.5	1	1	2.5
121 - Woodside Rd.	3	2	0.5	0.67	1	2.17

Based on the calculation of the public feedback score, El Camino Real ranked the highest with a score of 2.6 and Vera Avenue ranked the second highest with a score of 2.5. One of the

Maple Street projects, the Madison Avenue project, and the U.S. 101 underpass between Seaport Boulevard and Veterans Boulevard all ranked the lowest with a score of one. Figure 34 shows a map of all proposed projects and how they scored in terms of public feedback.

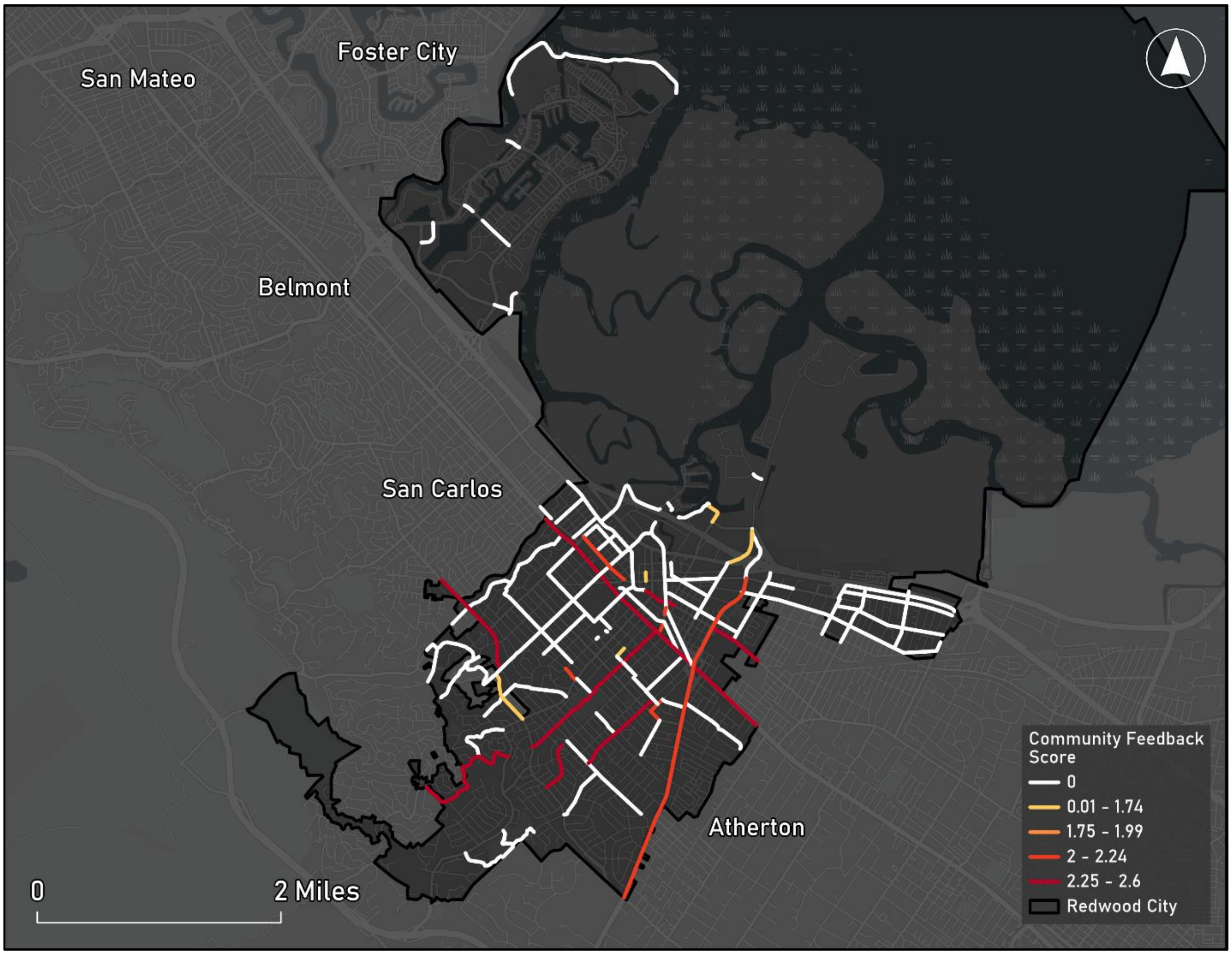


Figure 34. Proposed project community feedback scores

4.3 Equity Impact Quantification

A *ModelBuilder* tool was developed to assign each proposed project with a score that quantified how well it addressed geographic areas that have been historically underserved, socially and economically, using input from large community stakeholders (C/CAG, SamTrans, MTC EPC, and CAHPI as described in section 3.4). Each proposed project received a score of zero, one, two, three, or four. One point was given for each equity polygon dataset that the proposed project intersected. Figure 35 shows the equity score of each proposed project, derived from the number of community stakeholder equity polygon datasets each proposed project intersected with.

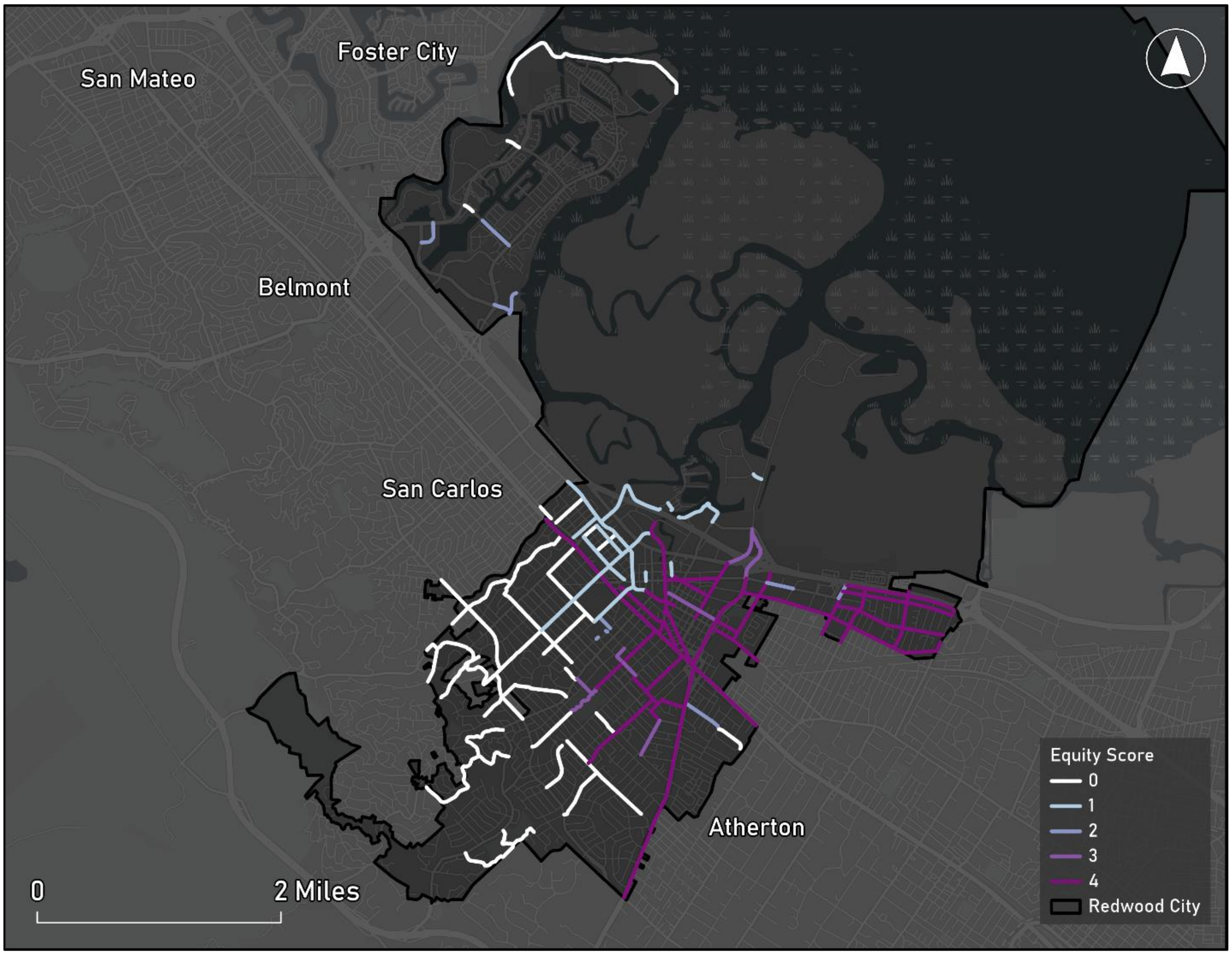


Figure 35. Proposed project equity scores

Proposed projects that score higher in equity impact have more avenues to external funding and help push the equity-related agendas of community stakeholders. Proposed projects that scored a four are concentrated on the eastern side of the city. The proposed projects on the western side of the city scored lower with many projects receiving a score of zero.

4.4 Site Selection

Following the development of a bikeability score that was interpolated from street segments to each of the proposed projects, a score that quantified workshop feedback, and a score that describes the extent to which each proposed project addresses issues of equity, the site selection process was undertaken. A weighted sum methodology was used to compute a final score that would rank the proposed projects in order of implementation priority. Figure 36 shows the location of each proposed project as well as how it ranked in terms of prioritization score.

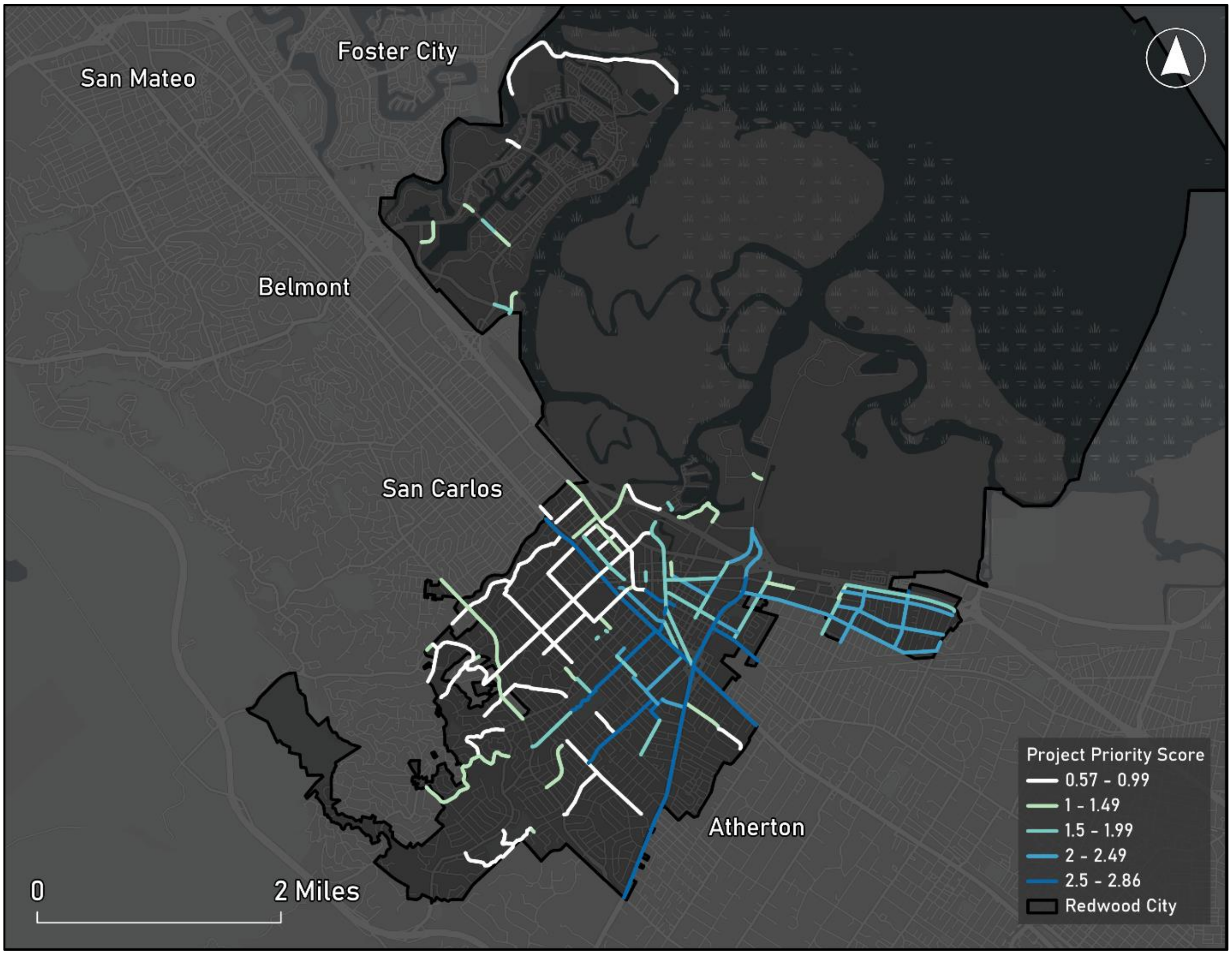


Figure 36. Proposed project prioritization scores

Table 13 shows the bikeability, equity, workshop, and priority scores of the top-15 ranking proposed projects in terms of priority score.

Table 13. Fifteen highest-scoring proposed projects in terms of prioritization

Project Name	Bikeability Score	Equity Score	Workshop Score	Priority Score
59 - Redwood Ave.	2.36	4	2.25	2.86
74 - Vera Ave.	2.09	4	2.50	2.86
113 - El Camino Real	1.98	4	2.60	2.86
82 - Hudson St.	2.47	4	2	2.82
72 - Poplar Ave.	2.40	4	2	2.79
122 – Maple St.	2.36	4	2	2.78
37 – Middlefield Rd.	2.06	4	2.25	2.76
120 – Middlefield Rd.	2.06	4	2.25	2.76
121 – Woodside Rd.	2.05	4	2.17	2.73
12 – Path through Red Morton Park	2.80	3	2.25	2.68
111 – Middlefield Rd.	1.68	4	2.25	2.64
8 - US 101 overcrossing at Haven Ave.	3.76	4	0	2.56
17 - Maple St.	1.50	4	2	2.50
24 – Marsh Rd.	3.17	4	0	2.35
78 – Second Ave.	2.86	4	0	2.27

The project goal was to create design proposals for the three highest-ranking projects in terms of priority score. Redwood Avenue, Vera Avenue, and El Camino Real scored the highest. However, it would be redundant to make designs for proposed projects that already have designs completed by the city and cycling infrastructure improvements along El Camino Real have already been investigated during the development of the El Camino Corridor Plan (City of Redwood City 2017). As such, it was disregarded from this study and replaced by the fourth-highest scoring project, Hudson Street. Ultimately, Redwood Avenue, Vera Avenue, and Hudson

Street were selected as the proposed projects to be addressed by the design phase of the project. The locations of these three proposed projects are shown in Figure 37.

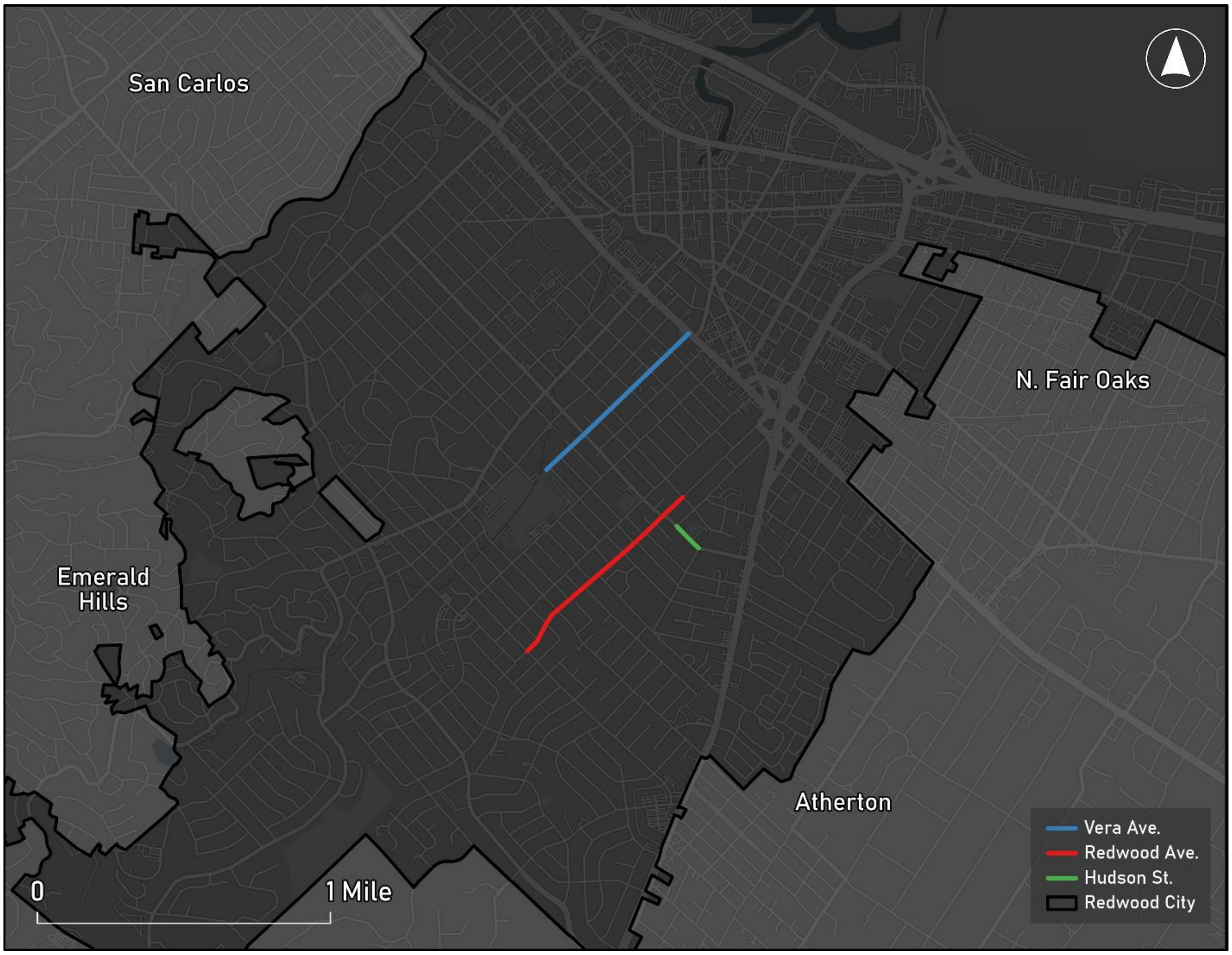


Figure 37. The three proposed projects selected to receive design proposals

4.5 Proposed Project Design Proposals

In this section, the final designs for each of the three projects are described and justifications for the design decisions are provided. For each of the three projects, there are three maps that illustrate the surrounding context, a StreetMix design for the street as it appears in the present, a StreetMix design for the new street design, and two renderings of the final SketchUp model.

4.5.1 Redwood Avenue

The Redwood Avenue proposed project addresses a segment of Redwood Ave. that runs 3,971 feet from Virginia Avenue at the southwest to Ebener Street at the northeast and is approximately 60 feet wide, including sidewalks. Redwood Ave. runs parallel to Oak Avenue, which is one block to the northwest. Roosevelt Avenue also runs parallel to Redwood Ave. and is located two blocks to the northwest. Roosevelt Ave. is considered an arterial route and receives considerably more automotive use than Redwood Ave. The site is shown in Figure 38. Redwood Avenue proposed project site

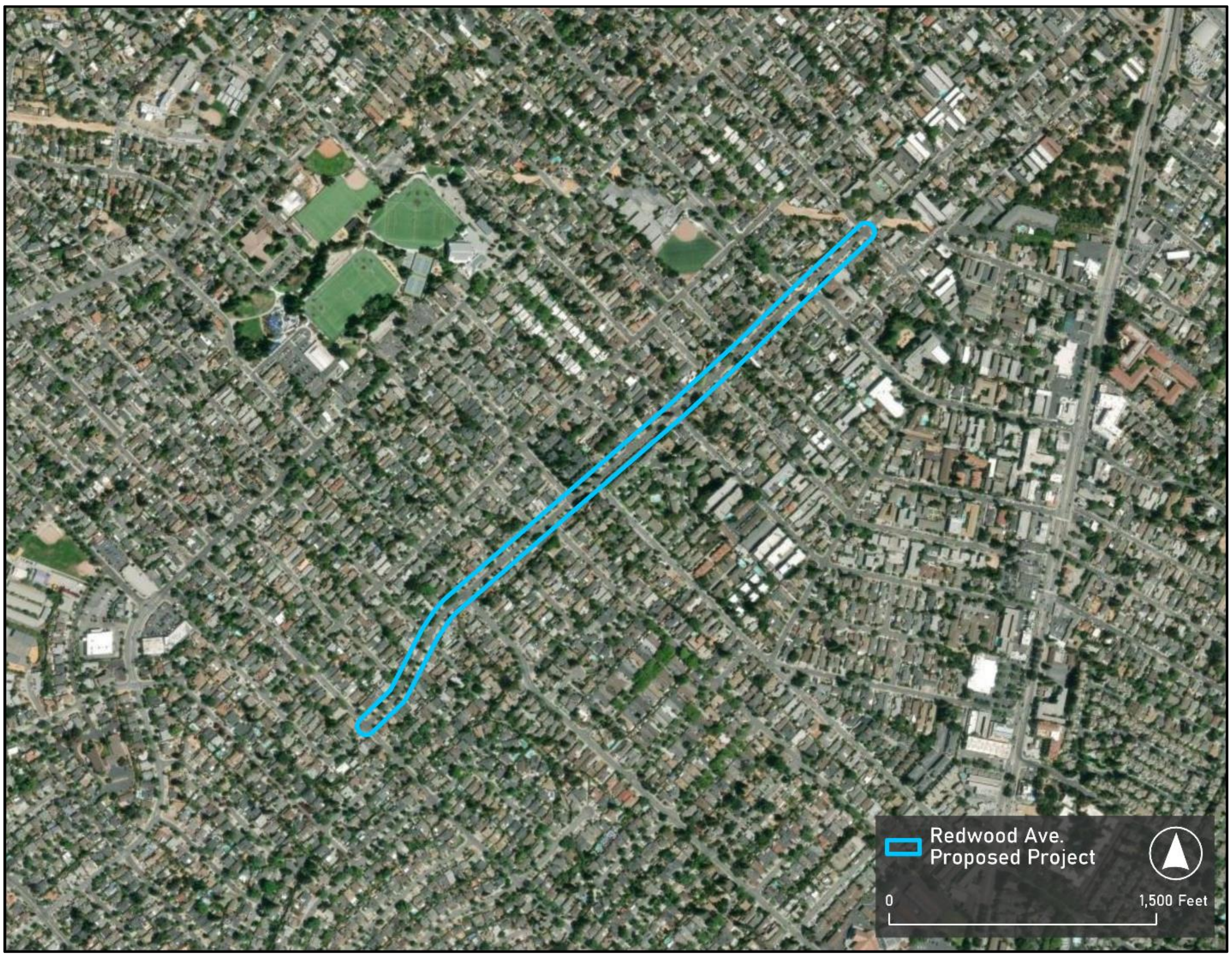


Figure 38. Redwood Avenue proposed project site

The northeast terminus of the Redwood Ave. proposed project is near a number of amenities including Hawes Elementary School, Hawes Park, a church, Palm Park, the Sequoia YMCA, and dining and retail along Woodside Road. The southwest terminus of Redwood Ave is two blocks from Roosevelt Center, which is a shopping center featuring dining, retail, groceries, and more. The Roosevelt Center is also adjacent to a church, public library, and Roosevelt Elementary School. Improved cycling infrastructure along the entire extent of the Redwood Ave. proposed project would make these amenities, which can be seen in Figure 39, easier to access using non-car means of transportation.

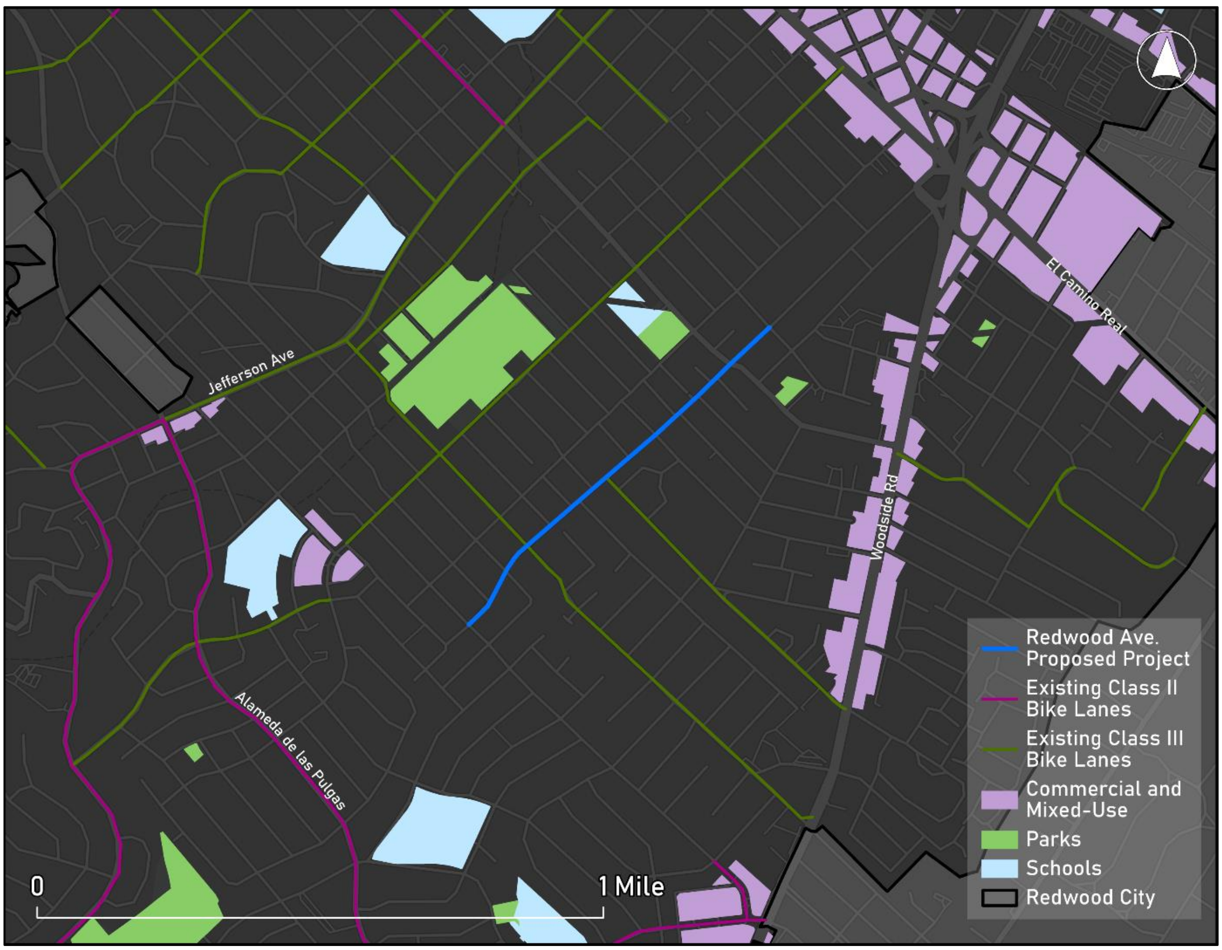


Figure 39. Amenities near the Redwood Avenue proposed project

Nearly all of the parcels along the proposed Redwood Ave. project are zoned for duplex residential use (Figure 40). While more densely populated than single-family zoning, duplex-heavy neighborhoods are not as densely populated as multi-family zoned areas. Most duplex homes do not have parking garages like multi-family buildings, and ample street parking may still be required. Additionally, many of the homes along this portion of Redwood Ave. are single-family homes, despite the duplex designation.

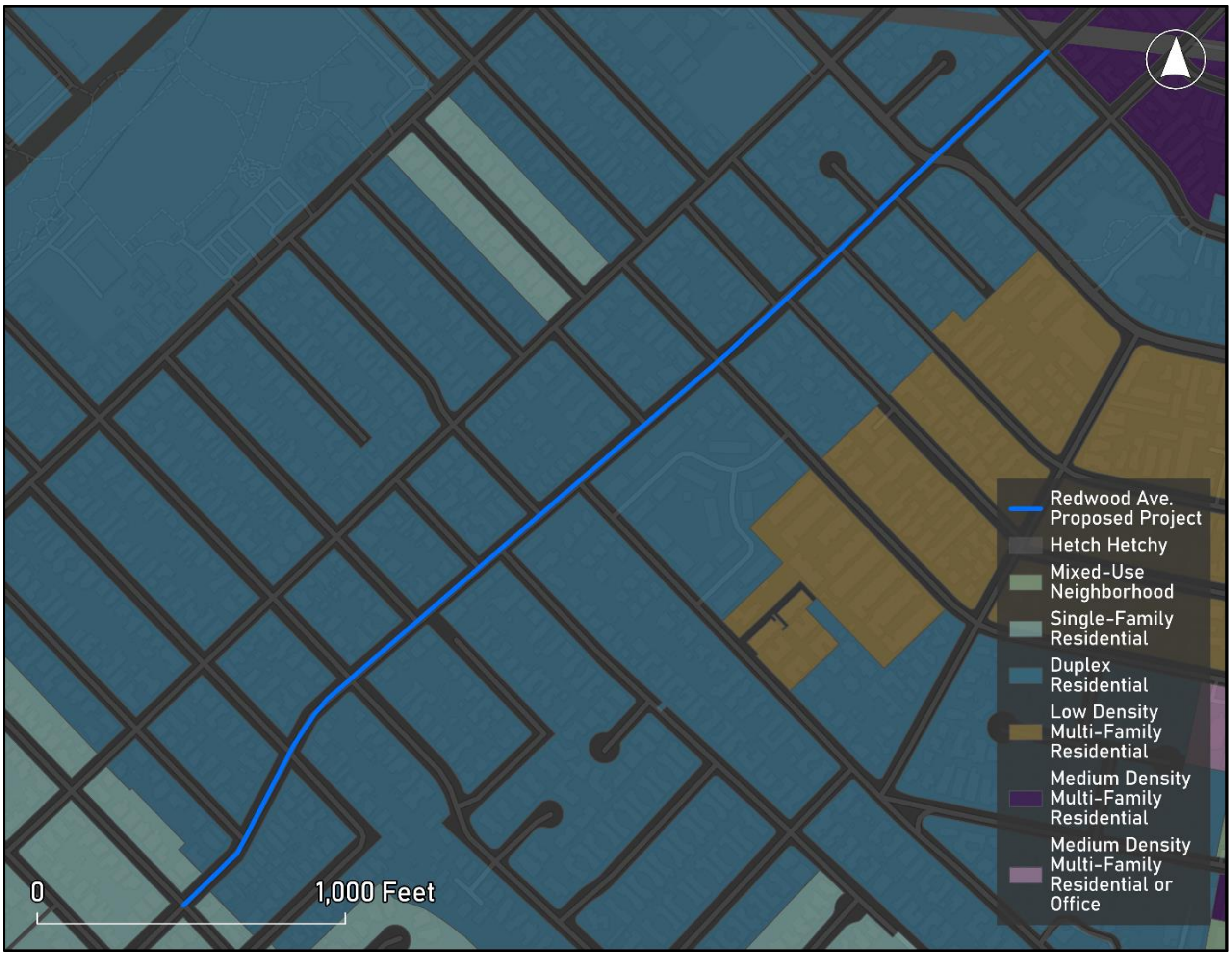


Figure 40. Zoning designations near the Redwood Avenue proposed project

Figure 41 shows a StreetMix visual of Redwood Ave. as it appeared in 2023 (Figure 41, top) and the proposed design with an emphasis on improving bikeability (Figure 41, bottom).

The redesign features a two-way bike lane that is protected from traffic by a 0.6m wide curb and a car parking lane.

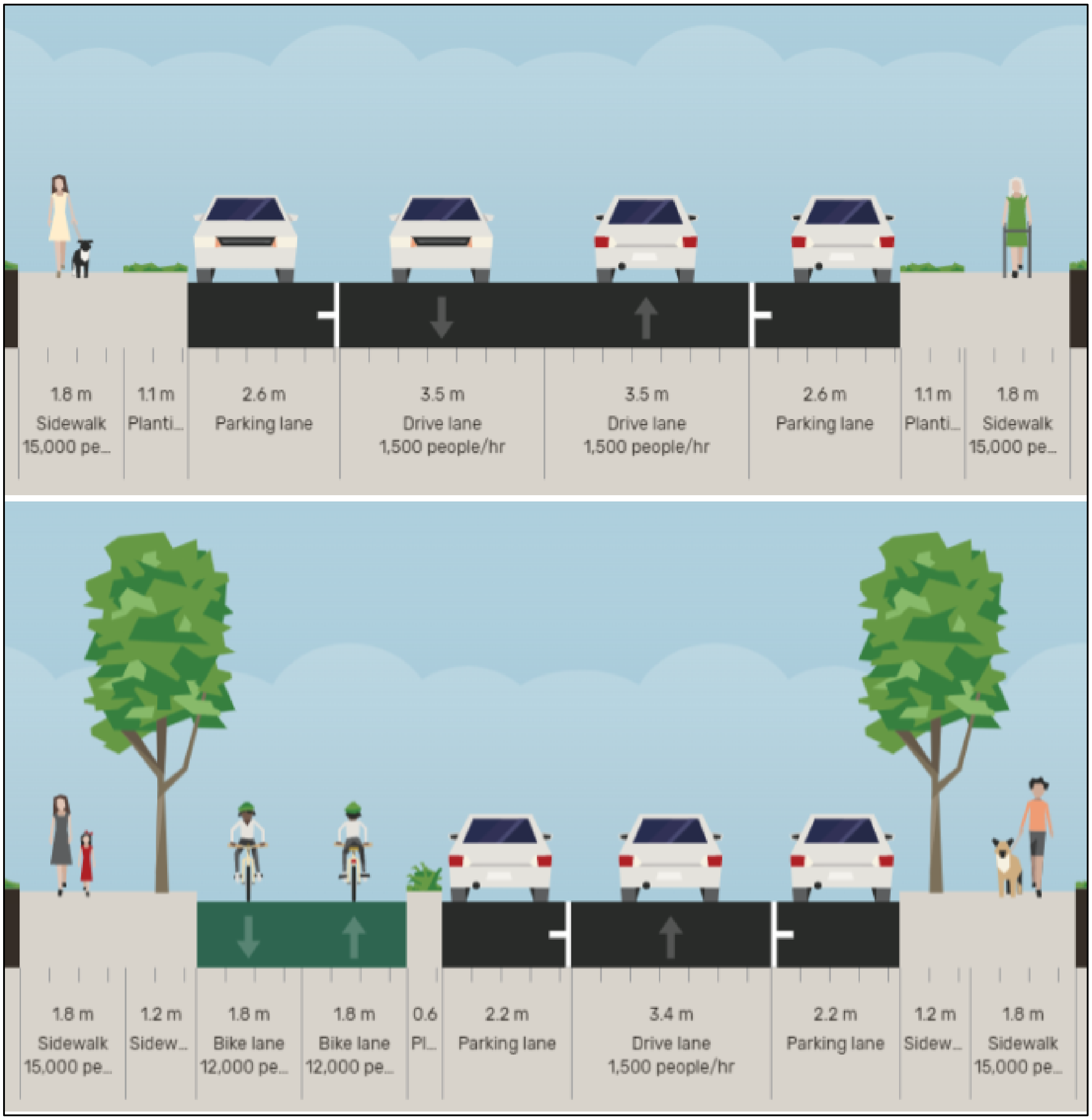


Figure 41. Redwood Ave. illustration of 2023 (top) and as proposed (bottom)

Figure 42. Redwood Avenue redesign aerial view shows a rendering of the Redwood Avenue redesign made in SketchUp.

Figure 42. Redwood Avenue redesign aerial view

Figure 43. Redwood Avenue redesign perspective view shows an eye-level rendering of the Redwood Avenue redesign made in SketchUp.

Figure 43. Redwood Avenue redesign perspective view

The Redwood Ave. redesign shifts the road from a two-way street to a one-way street. There is precedent for this type of infrastructure change, exemplified by the western end of Colorado Avenue in Santa Monica, CA. According to reports about the Colorado Ave. shift to one-way traffic, "The [traffic] study acknowledged that one-way travel would 'result in potentially additional traffic redistribution.' But it found 'these traffic shifts can be fully accommodated by the given traffic capacity [on] parallel corridors, without creating significant operational issues or travel delays'" (Chandler 2013). As mentioned, Redwood Ave. runs parallel to Oak Ave. and Woodside Road and Roosevelt Ave., which already receive more use. Therefore sufficient options should remain for drivers who may have previously driven in both directions along Redwood Ave.

The designed one-way street would run from the northeast towards the southwest, which was an intentional decision. First, it funnels cars towards the Roosevelt Center, which is one of the few commercial areas in Redwood City not located on or near El Camino Real or Woodside Road. More use of the Roosevelt Center's facilities could inspire future growth around it, resulting in a walkable community. Additionally, restricting travel towards the Roosevelt Center may result in economic losses for the businesses that use that space.

In the Redwood Ave. redesign, the existing sidewalks and sidewalk buffers would be maintained. The bike lanes would be located on the southeast side of the street and would be made up of a two-way Class IV bike lane, with each lane occupying nearly six feet of space. The bike lane is painted green to signify its use, and the green coloring extends through intersecting roads and driveways. A concrete curb would be constructed to provide protection for the bikers and would be almost 2 feet wide and 6 inches high. The rest of the street would consist of a 7.2-foot-wide parking lane on either side of an 11-foot-wide driving lane, which physically permits access by emergency vehicles.

4.5.2 Vera Avenue

The Vera Avenue proposed project addresses the segment of Vera Ave. that runs 3,557 feet from Red Morton Park at the southwest to El Camino Real at the northeast and is approximately 60 feet wide, including sidewalks. At the southwest terminus, there is a paved bike and pedestrian path that provides access into Red Morton Park. Across El Camino Real at the northeast terminus is Maple Street, which features a Class IV bike lane. The site is shown in Figure 44. Vera Avenue proposed project site.

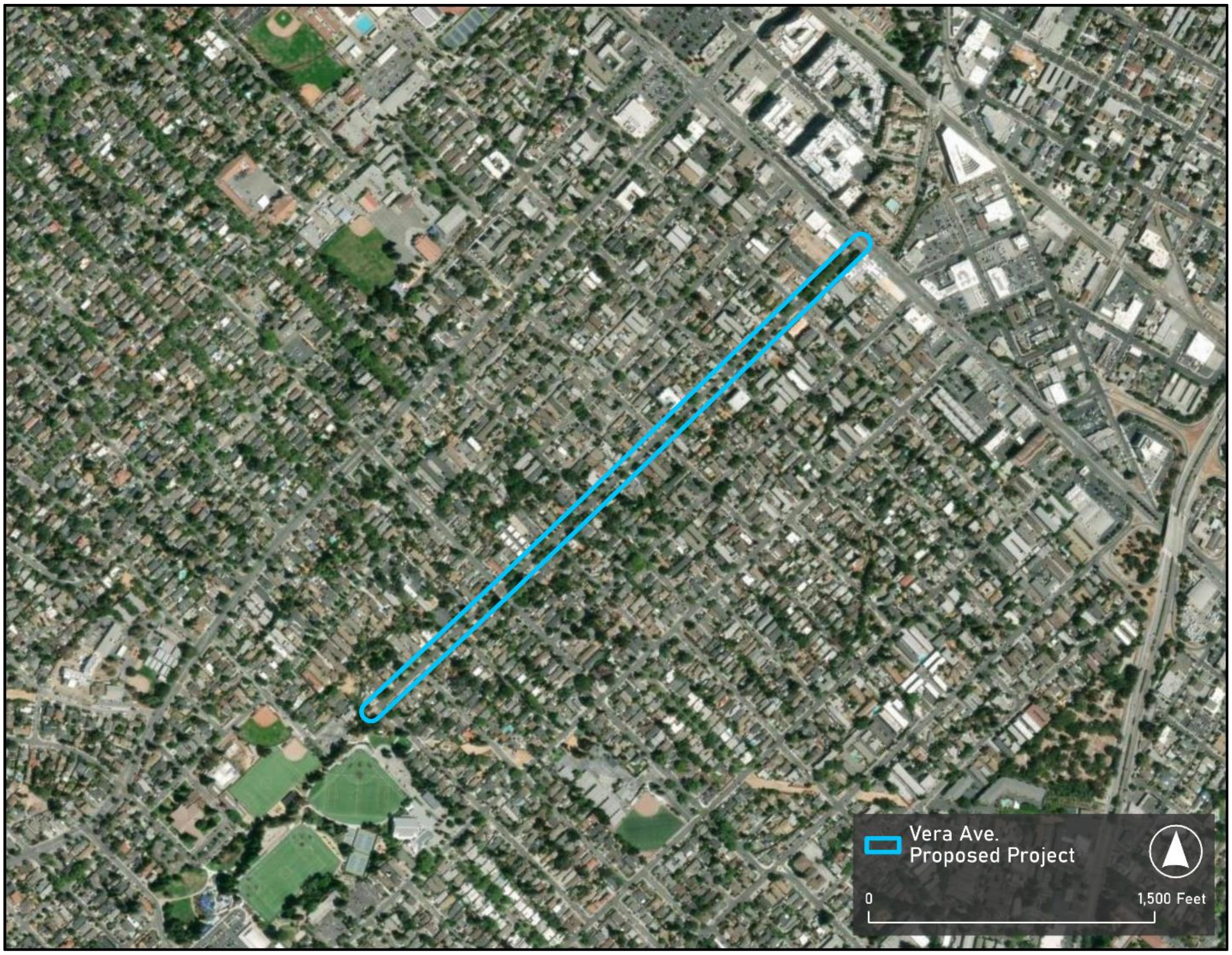


Figure 44. Vera Avenue proposed project site

The immediate area around the northeast end of Vera Ave. features an abundance of mixed-use facilities, both existing and under construction as of 2023. Additionally, one of Redwood City's three existing Class IV bike lanes, as of 2023, is on Maple Street, quite close to Vera Ave. Just beyond the immediate vicinity of the mixed-use facilities is the Redwood City CalTrain and SamTrans station as well as downtown Redwood City. Furthermore, Vera Ave. is mere blocks away from schools such as John Gill Elementary School, Hawes Elementary School, and Sequoia High School. A redesign of the street's infrastructure that maximizes bikeability would make it theoretically possible for residents of the neighborhood to have safe and efficient access to schools, park space, retail, and public transportation and accomplish daily business without using a car. Figure 45 visualizes the existing amenities in the area surrounding the proposed Vera Ave. project.

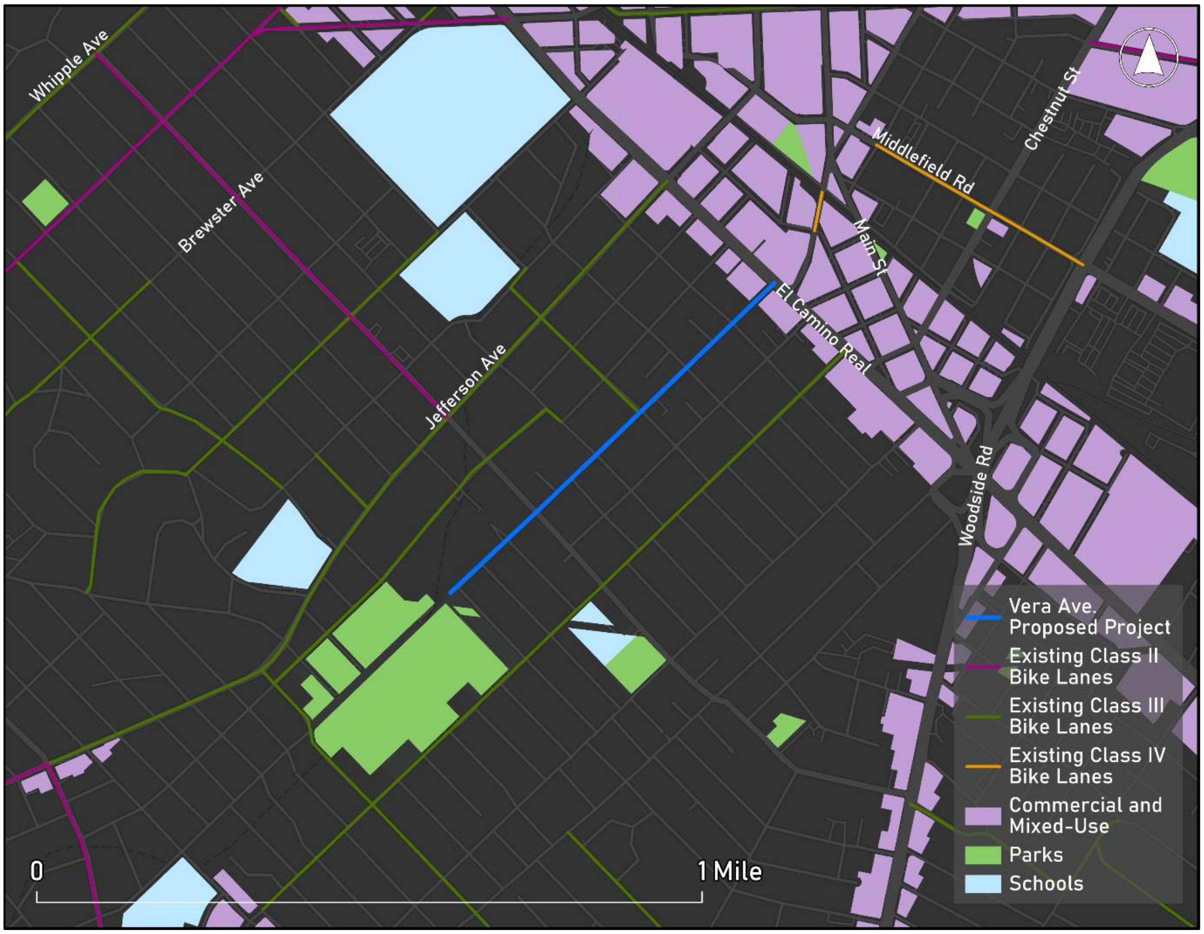


Figure 45. Amenities near the Vera Avenue proposed project

City zoning designations have a significant impact on the design of the Vera Ave. cycling infrastructure. Zoning for the Vera Ave. study area is shown in Figure 46. The northern half of the Vera Ave. proposed project is flanked by medium density multi-family residential zoning. The southern half is flanked by duplex residential housing. These zoning designations imply a relatively high density. Multi-family housing also often implies the existence of sufficient on-site parking, whether as a garage or large driveway. While as of 2023, many of the parcels zoned for multi-family housing feature single-family homes, an increase in population and development will likely result in more multi-family options on Vera Ave. For this reason, the decision to remove street parking from one side of the street was made. This decision is supported by the fact that improved cycling infrastructure, as well as the fact that there is potential for a highly bikeable route between Vera Ave. and the Redwood City CalTrain station, should promote cycling as a primary means of transportation over driving and reduce the need to own a car.

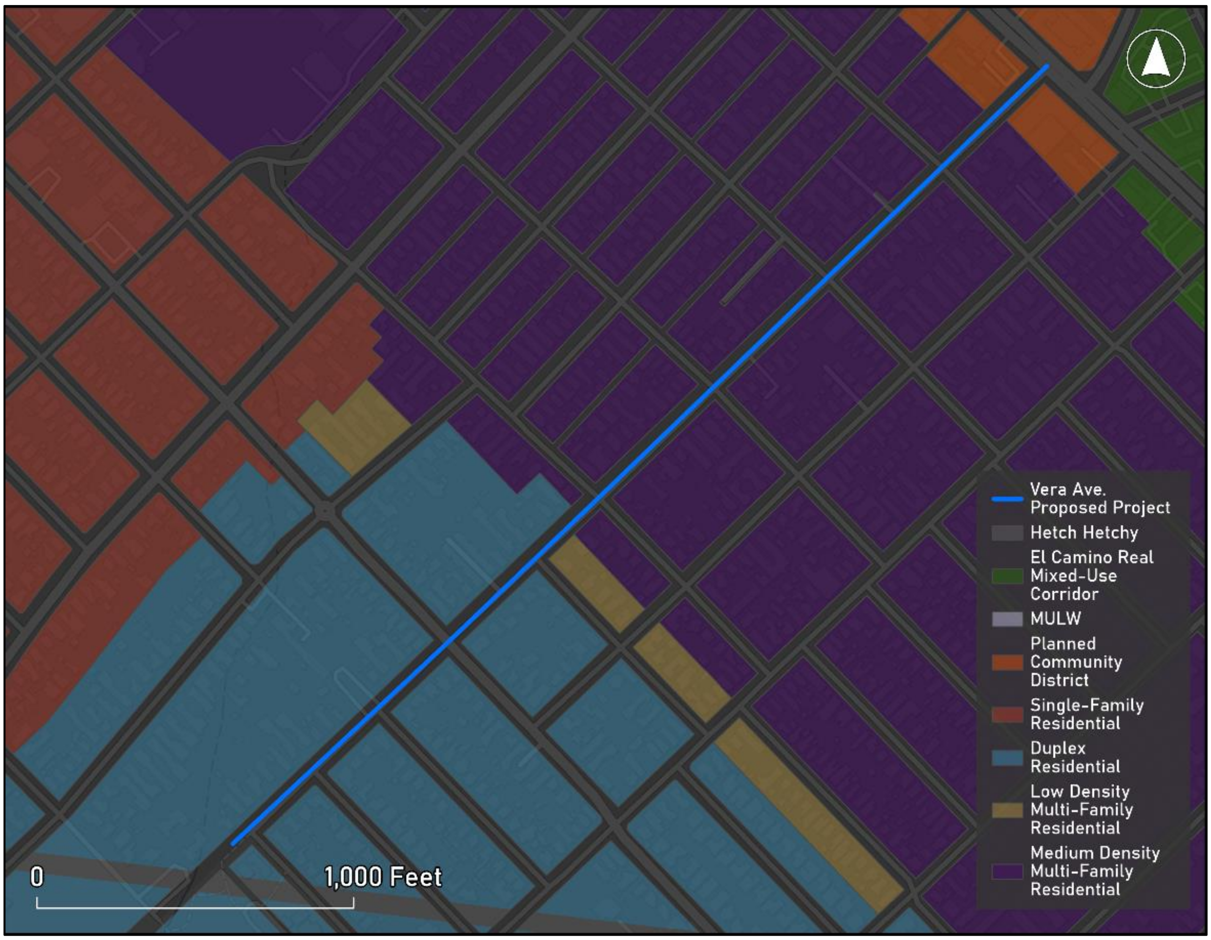


Figure 46. Zoning designations near the Vera Avenue proposed project

Figure 47 shows a StreetMix illustration of Vera Avenue as it appeared in 2023 (Figure 47, top) and a StreetMix illustration of the redesign of Vera Ave. with an emphasis on improving bikeability (Figure 47. Vera Avenue redesign in StreetMix, bottom). The redesign includes a two-way protected bike lane with protection coming from a 0.4m wide curb and a parking lane.

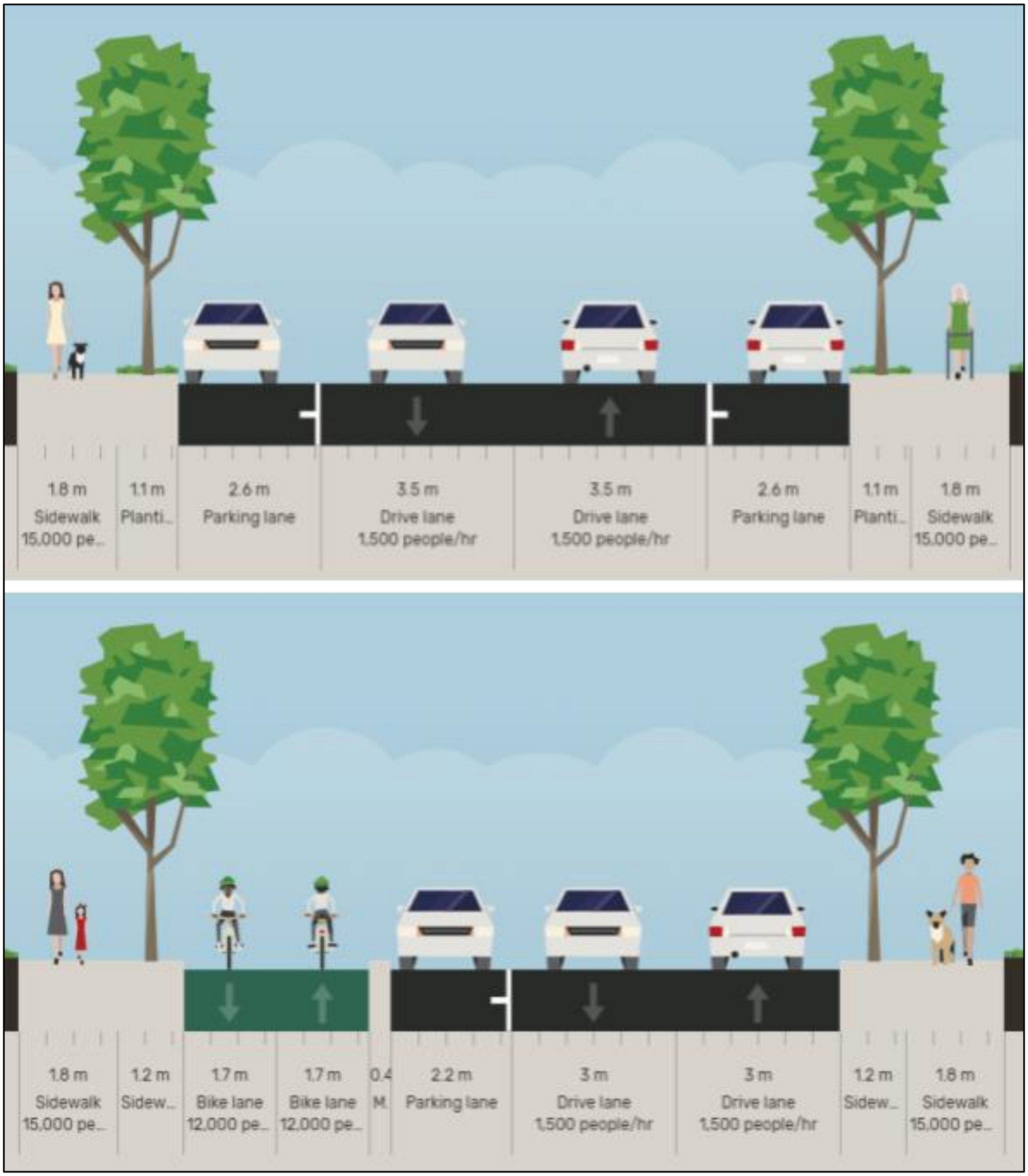


Figure 47. Vera Avenue redesign in StreetMix

Figure 48. Vera Avenue redesign aerial view shows a rendered view of the Vera Avenue redesign from above.

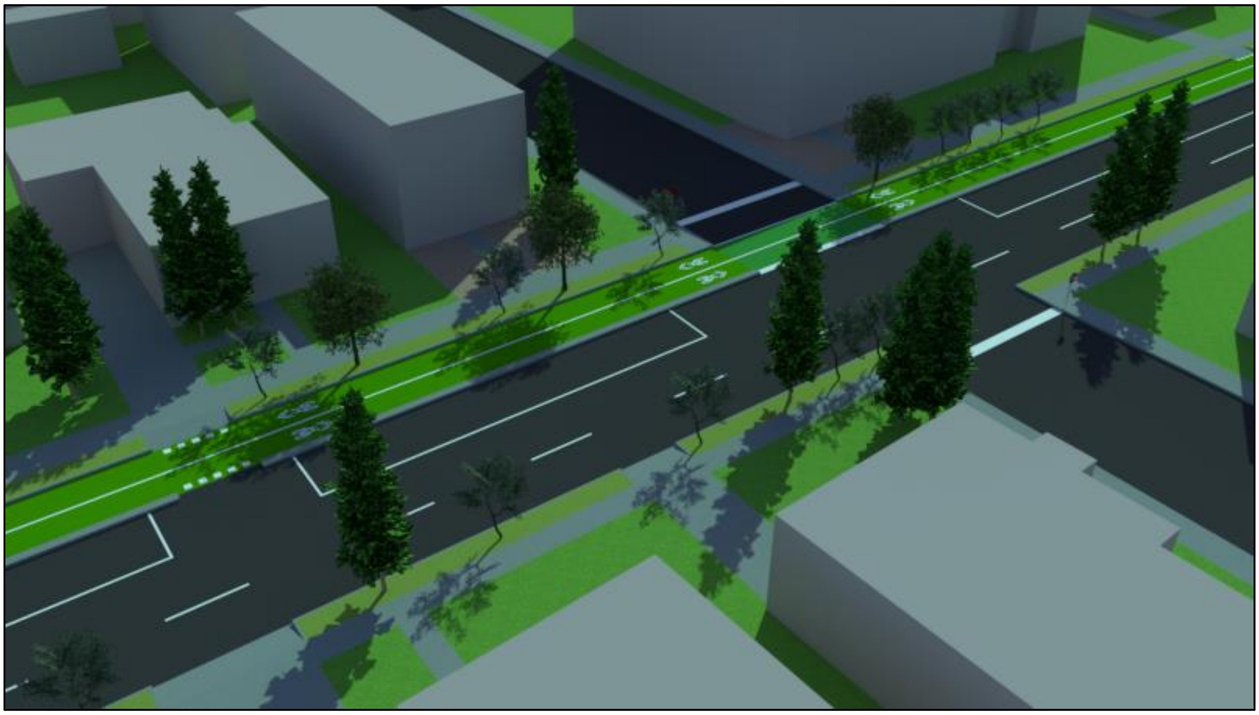


Figure 48. Vera Avenue redesign aerial view

Figure 49. Vera Avenue redesign perspective view shows an eye-level rendering of the Vera Avenue redesign created in SketchUp.

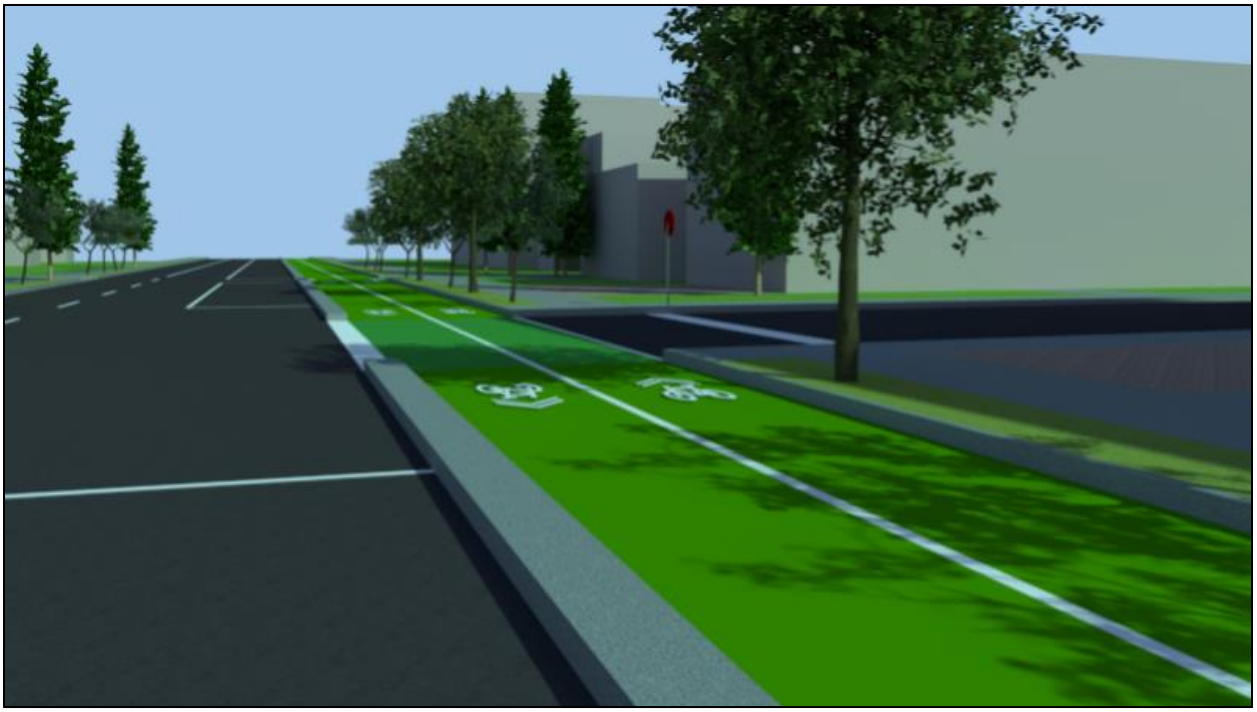


Figure 49. Vera Avenue redesign perspective view

In the Vera Ave. redesign, the sidewalks and sidewalk buffers on both side of the street are maintained. The street parking on the southeast side of the road is replaced by a two-way, fully-protected, green-painted bike lane, with each lane traveling in opposite directions and taking up just over 5.5 feet of width. Adjacent to the bike lane is a concrete curb with a width of 1.3 meters and a height of six inches. This barrier, albeit not tall, provides a clear divider between bike space and car space. Next to the barrier is space for street parking. The designated street parking space takes up 7.2 feet of width and is accessible to cars traveling towards El Camino Real. The street parking was chosen to remain on the southeast side of the street as parked cars can complement the concrete curb as a means of providing cyclists with physical protection. Furthermore, parked cars will be facing northeast while cyclists in the adjacent lane will be traveling southwest. This creates an opportunity for direct eye contact between cyclists and parked drivers, increasing awareness in both the driver and cyclist and reducing the risk of a parked car’s door opening suddenly in front of the cyclist. The rest of the street is made up of two automotive lanes, one traveling in each direction. Each lane is just under 10 feet wide, and there is sufficient space for emergency vehicles to continue to use Vera Ave. While this means that cars will be driving right next to the sidewalk, pedestrians should be able to remain safe given the sidewalk buffer, inclusion of traffic calming measures such as speed bumps, and the option to walk on the southeast sidewalk. This design is intended to run the entire extent of Vera Ave., providing access into Red Morton Park as well as to El Camino Real. In the future, cycling infrastructure could be implemented across El Camino Real and extend connectivity to the preexisting Class IV bike lanes on Maple Street.

4.5.3 Hudson Street

The Hudson Street proposed project addresses a segment of Hudson St. that runs 562 feet from Poplar Avenue to the northwest to Palm Avenue to the southeast and is approximately 60 feet wide, including sidewalks. While this project is relatively short, it serves as a continuation of infrastructure upgrades on segments of Hudson St. to the west. The site is shown in Figure 50.

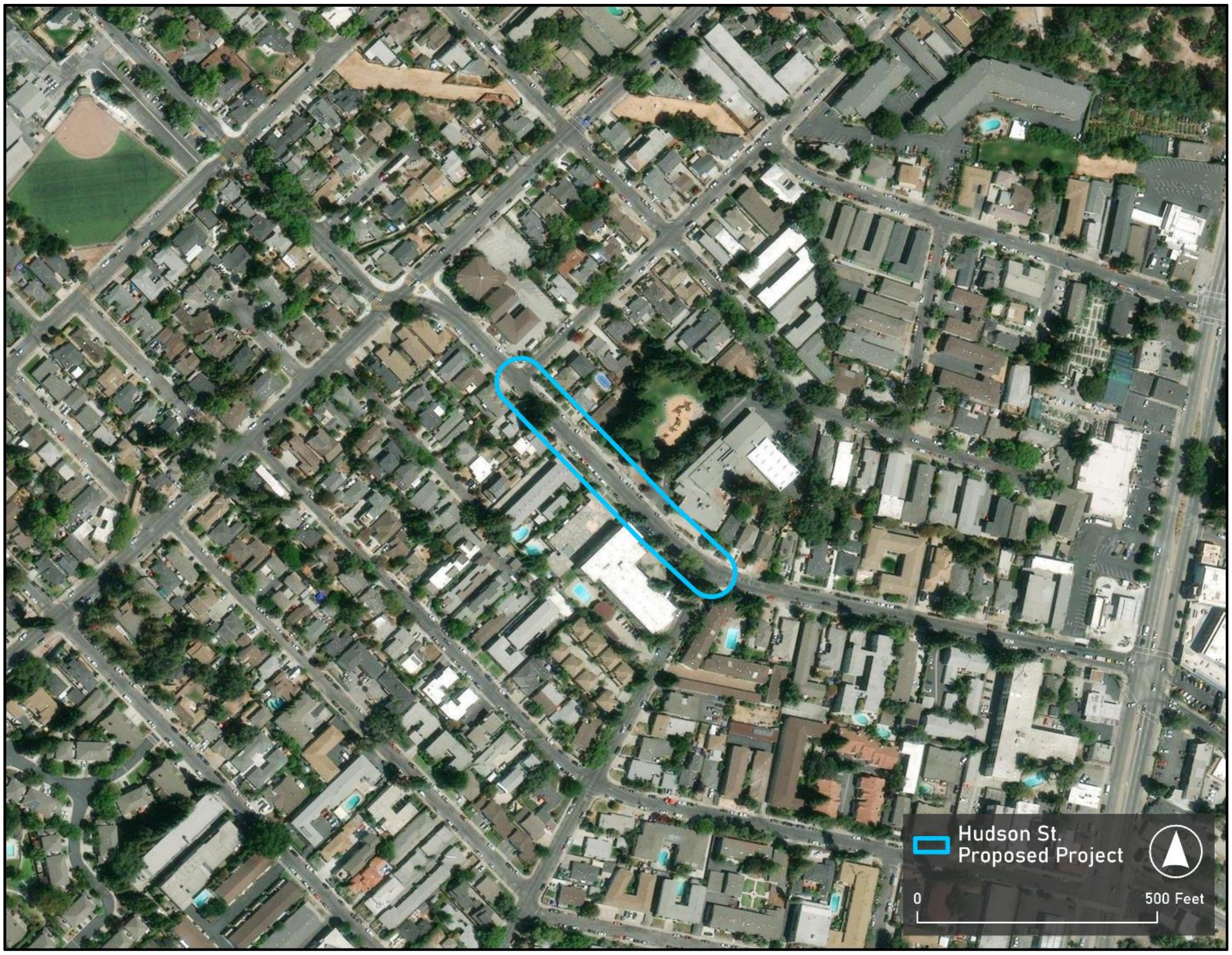


Figure 50. Hudson Street proposed project site

The proposed project is one block to the west of Woodside Road, which is a popular artery for automotive travel and features significant retail and dining opportunities. The stretch of Hudson St. addressed by this proposed project contains Palm Park, which features a large grass area and a play structure, as well as the Sequoia YMCA. Both of these amenities are on the northern side of the street. One block to the west is a church, while two blocks to the west are Hawes Park and Hawes Elementary School. Figure 51 shows some of the amenities near the Hudson St. proposed project.

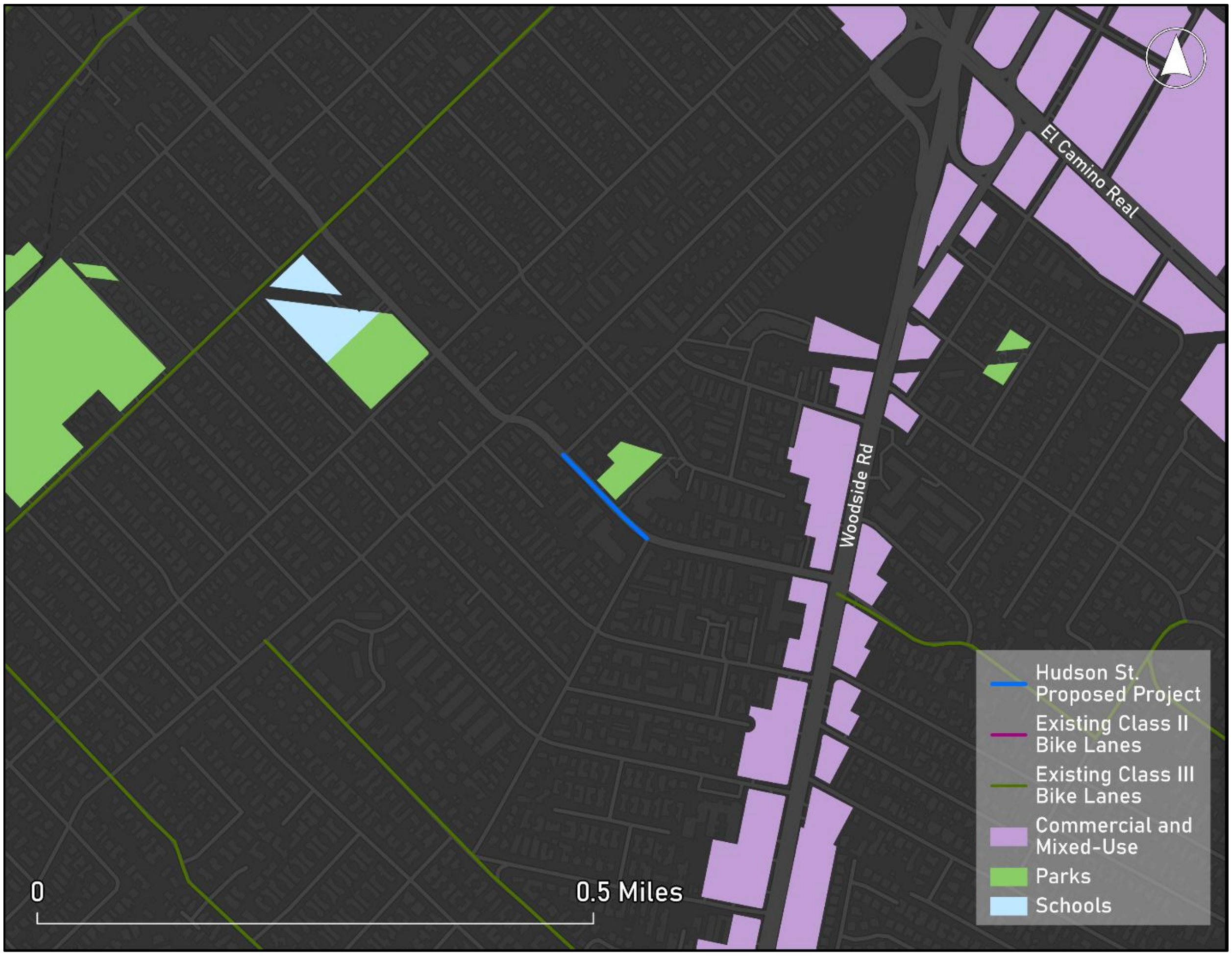


Figure 51. Amenities near the Hudson Street proposed project

In terms of zoning, the Hudson Street proposed project is flanked by a mixture of residential duplex and low-density multi-family residential designations, as seen in Figure 52. There are three lots zoned for low density multi-family residential along the southern edge of this segment of Hudson St. and each is built up quite extensively while also featuring on-site parking. However, despite the dense population surrounding this proposed project, all street parking was maintained.

Figure 52. Zoning designations near the Hudson Street proposed project

Figure 53 shows a StreetMix illustration of Hudson Street as it appeared in 2023 (Figure 53, top) and a StreetMix illustration of the Hudson St. with an emphasis on improving bikeability (Figure 53, bottom). The redesign includes a two-way bike lane with physical protection coming from parked cars. There is also room for bollards to be implemented, which is shown in the renderings.

Figure 53. Hudson Street redesign in StreetMix

Figure 54. Hudson Street redesign aerial view shows an aerial rendering of the Hudson Street redesign created in SketchUp.

Figure 54. Hudson Street redesign aerial view

Figure 55. Hudson Street redesign perspective view shows an eye-level perspective of the Hudson Street redesign created in SketchUp.

Figure 55. Hudson Street redesign perspective view

In the Hudson St. redesign, only the northern sidewalk and sidewalk buffer are preserved. The southern sidewalk is preserved; however, its buffer was removed to make more space for the bike infrastructure. Because the amenities found on this block, Palm Park and the Sequoia YMCA, are on the northern side of the street, the decision was made to place both directions of bike lanes on the northern side of the street. The two-way Class IV bike infrastructure is made up of one lane going in each direction, with each lane occupying nearly six feet of width.

Immediately to the south of the bike infrastructure is a seven-foot parking lane. It would likely be possible to install bollards to provide physical protection for cyclists, but parked cars are equally, if not more, protective. Similarly to the Vera Ave. design, parked cars and cyclists will be facing opposite directions, minimizing the risk of cyclists being hit by suddenly opening car doors. To the south of the first parking lane are two lanes for automotive travel, one going in each direction. Each of these lanes is 10 feet wide. Finally, to the south of these lanes is another parking lane, which is also seven feet wide.

Chapter 5 Conclusions

A geodesign methodology was applied to support the advancement of bicycle infrastructure in Redwood City, California. As geodesign is a complex multidisciplinary and iterative practice, several research questions were answered and ultimately woven together to produce a set of final output. This chapter summarizes the results and key takeaways of each component of the project, while also emphasizing the utility of an interdisciplinary geodesign methodology for evaluating and advancing bikeability. In addition, considerations will be made to the limitations of this project as well as what future work, both in Redwood City and more broadly, may entail.

5.1 Bikeability Quantification

Quantifying bikeability for each street segment in Redwood City yielded interesting results. In general, bikeability was found to be between low and moderate. However, there are a few neighborhoods which support moderate to high levels of bikeability. Furthermore, there is disconnect between Redwood Shores and the rest of Redwood City, which may dissuade commuters from travelling between the two areas on bike. While Redwood Shores features high levels of bikeability, it is isolated and realistically only provides significant utility and value to intra-Redwood Shores cyclists. Redwood City’s bike network has significant opportunities to expand, which can be done by connecting the communities that already support high bikeability with improved infrastructure.

The bikeability quantification is validated by comparing the results of the Redwood City analysis with the results of Winters’ 2013 study, which is outlined in section 2.3.2. Unlike this project, Winters used a weighted overlay technique which resulted in a continuous raster that quantified bikeability at any given location within the Vancouver study area. However, Winters used similar input variables, including topography, destination density, and bike route access. Winters' results matched up with the results of this paper, indicating that bikeability is often higher in downtown areas where there is already existing cycling infrastructure as well as an abundance of locations worth cycling to, such as stores and restaurants. In addition, low bikeability can often be found in areas with significant hilly terrain and minimal destination opportunities. While the methodology used by Winters and in this study differed slightly, the results do in fact validate each other.

Despite the success of the bikeability evaluation, it is important to consider a possible limitation. It is challenging to ever be able to confirm whether the ideal configuration of weights and scaled values was used in a GIS multi-criteria decision analysis, however referencing literature, and soliciting feedback on the configuration and results can help optimize the weight and scale decisions (Ryan and Nimick 2019).

5.2 Workshop

Conducting stakeholder engagement is a critical component of any geodesign project. It is important to query the people of the place and find out what their wants and needs are for their area. Failing to do so may result in poor designs or underutilized public spaces.

The workshop for this project was well-planned and ran smoothly, resulting in valuable input from the local stakeholders who were in attendance. Throughout the workshop, the nine participants who attended the entirety of the session remained engaged and demonstrated thoughtful and collaborative thinking. 24 proposed projects were mentioned as feasible locations for improved bikeability and while 24 proposed projects may appear low given the number of total streets in Redwood City, one explanation is that the participants were seemingly united in terms of identifying roads that they believed would be useful as cycling corridors. This is further suggested by the fact that many of the streets had multiple mentions. Moreover, the relatively small number of participants as well as the length of the workshop (1.5 hours) may have contributed to the small number of mentioned streets.

In addition, it seemed as if all the participants were extremely pro-cycling and therefore it was impossible to facilitate discussions with significant disagreement. Nobody voiced opinions in favor of cars or against a complete overhaul in favor of cycling infrastructure, and it is likely that some residents of Redwood City do share that sentiment. Workshop bias could have been prevented by targeting more people from broader backgrounds. But overall, the workshop proved successful and was an integral part of this thesis.

5.3 Equity Analysis

A GIS methodology was used to evaluate the extent to which each proposed project would interact with communities that have historically been underserved, as evident by their demographics. This was done by acquiring four sets of polygon spatial data, each created by a different Bay Area stakeholder authority. Proposed projects were measured for the number of datasets that they overlapped, with a higher number of datasets indicating a stronger impact on resolving issues related to equity. Furthermore, a higher number of overlaps can also lead to an increase in the amount of funding that a proposed project receives from external sources. The methodology applied to conduct the equity analysis built off the work undertaken by Grisé and El-Geneidy (2018). Like their work, this thesis ensured the inclusion of equity considerations in the decision-making process regarding the placement of cycling infrastructure by using polygonal spatial data that represented disadvantage communities, based on various sociodemographic metrics.

This process was straightforward and yielded results that were to be expected based on previous investigations into the dispersion of demographic information throughout the city. Most of the equity polygons were located on the eastern side of the city, where median household income is relatively low and non-white percentage is relatively high, when compared to the western side of the city.

The relationship between equity and bikeability in Redwood City was further explored by analyzing demographics in conjunction with the results of the bikeability analysis. This allowed for an investigation into the relationship between bikeability and non-white percentage, zero-car households, and median household income.

5.3.1 Bikeability and Demographics in Redwood City

A better understanding of bikeability in Redwood City was achieved by using a bivariate symbology to view the bikeability results with demographic information at the block group scale. Bikeability appears to be overall higher in block groups where the percentage of households that do not own a car is higher, such as in neighborhoods 11, 12, and 14 (see Figure 56). This is a positive result, as when the number of households that do not own a car is relatively high, infrastructure that supports other means of transportation, such as cycling, should exist. However, neighborhoods seven. eight, 15, and 16 feature a high zero car household percentage but low bikeability (see Figure 56). These four neighborhoods are prime candidates to receive infrastructure investments that improve bikeability as a high zero car household percentage implies that the availability of other modes of transportation needs to be increased. The three proposed projects that underwent the design stage of this thesis are all within or adjacent to neighborhoods seven and eight (see Figure 56).

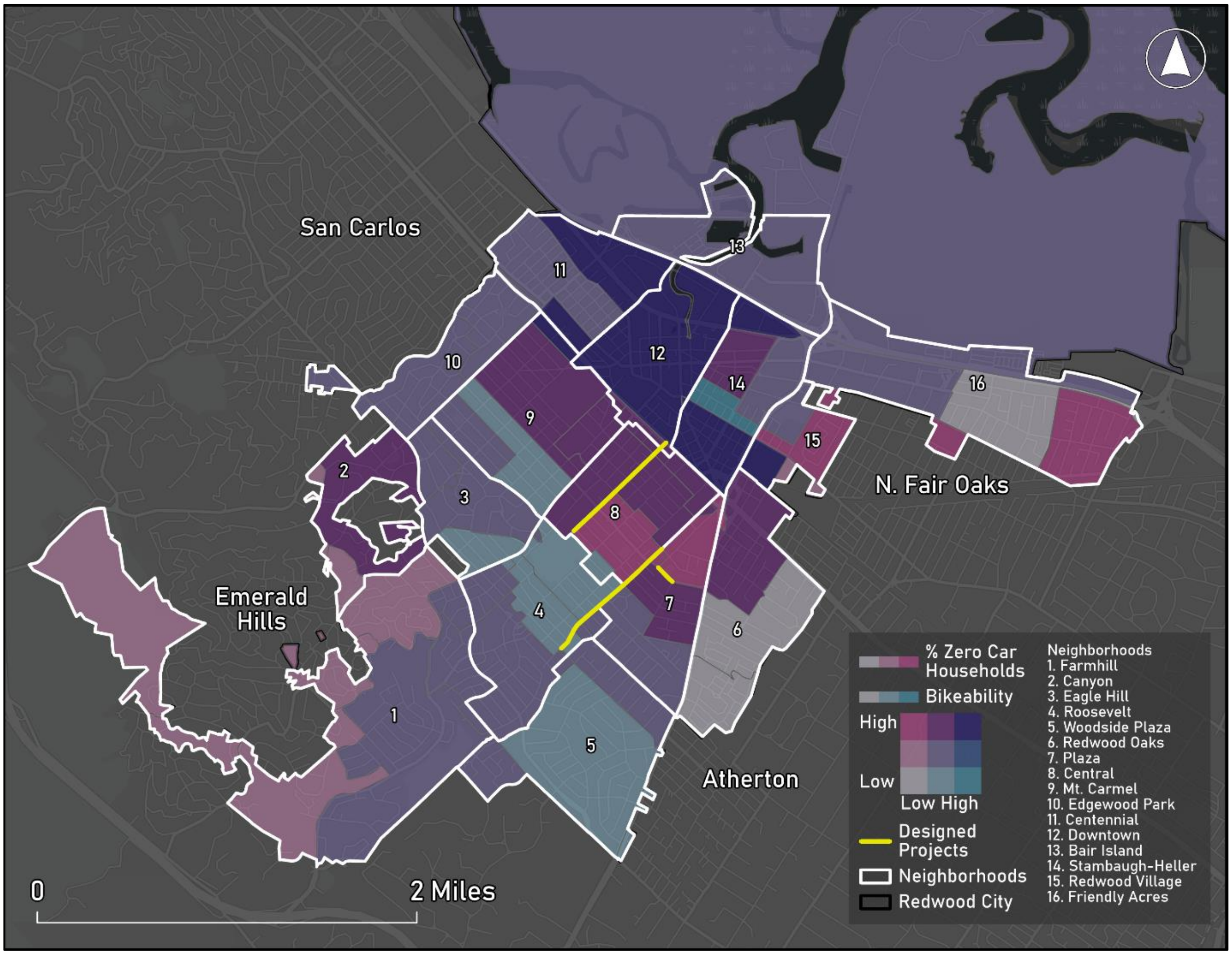


Figure 56. Bikeability and zero car household percentage in Redwood City

When comparing bikeability with median household income in Redwood City, a small correlation becomes apparent. While there is not a major relationship between overwhelmingly high bikeability and a high median household income, some of the higher income block groups on the western side of the city have slightly better bikeability. This is especially evident in neighborhoods three, nine, and 10 (see Figure 57). Alternatively, aside from neighborhood 14, most of the block groups that have the lowest median household income feature bikeability ranging from moderate to low (see Figure 57). The three proposed projects that received designs in this project are all within neighborhoods that feature a low median household income and low to moderate bikeability (see Figure 57).

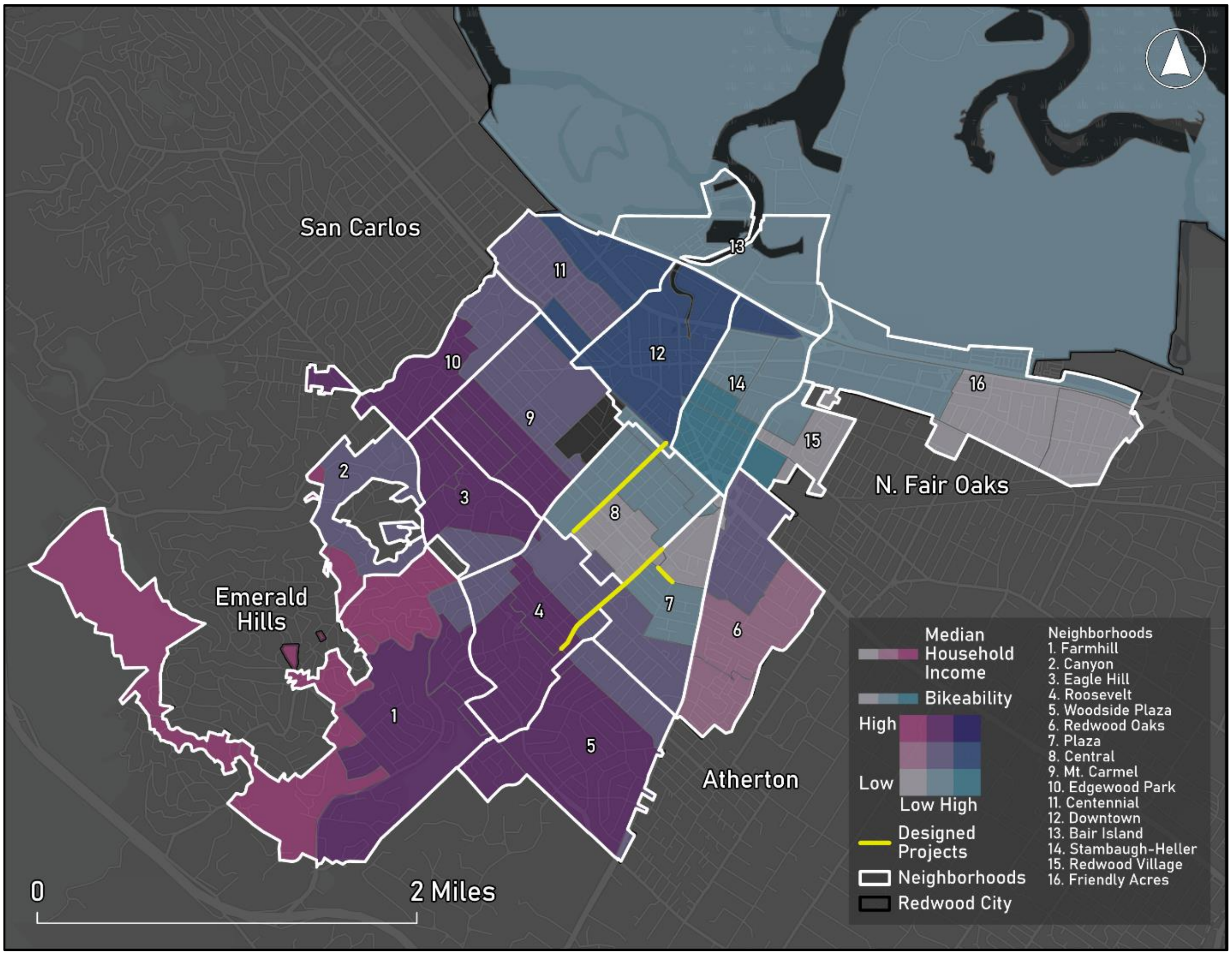


Figure 57. Bikeability and median household income in Redwood City

The relationship between non-white percentage and bikeability (Figure 58) is similar to the relationship between median household income and bikeability. Neighborhoods one, two, three, five, and nine have a lower non-white percentage and have moderately higher bikeability than other parts of the city. Neighborhoods six, eight, 15, and 16 have a higher non-white percentage and have generally moderate to poor bikeability, Neighborhood 14, where a Class IV bike lane was installed in 2022, has a high non-white percentage and a high level of bikeability.

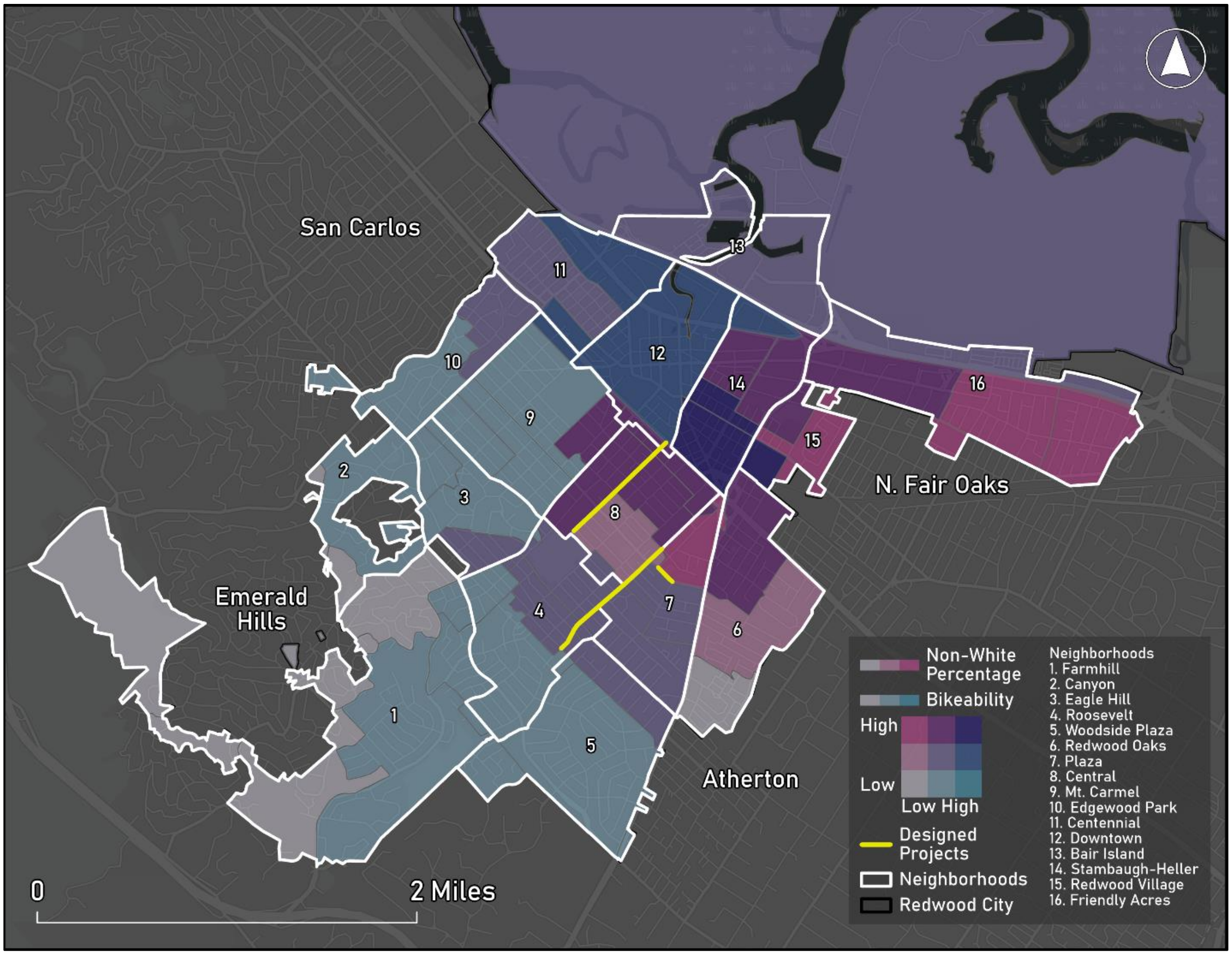


Figure 58. Bikeability and non-white percentage in Redwood City

5.3.2 Bikeability and Demographics in Redwood Shores

In contrast to Redwood City, block group demographics in Redwood Shores demonstrate, to some extent, homogeneity. There is minimal correlation between the small variation in demographics and bikeability, which makes sense given that the community was master planned, and its demographics had little, if any, impact on the allocation and distribution of infrastructure. There is not much variation in terms of households that do not own a car and the percent of zero car households in Redwood Shores ranges is fairly low (Figure 59).

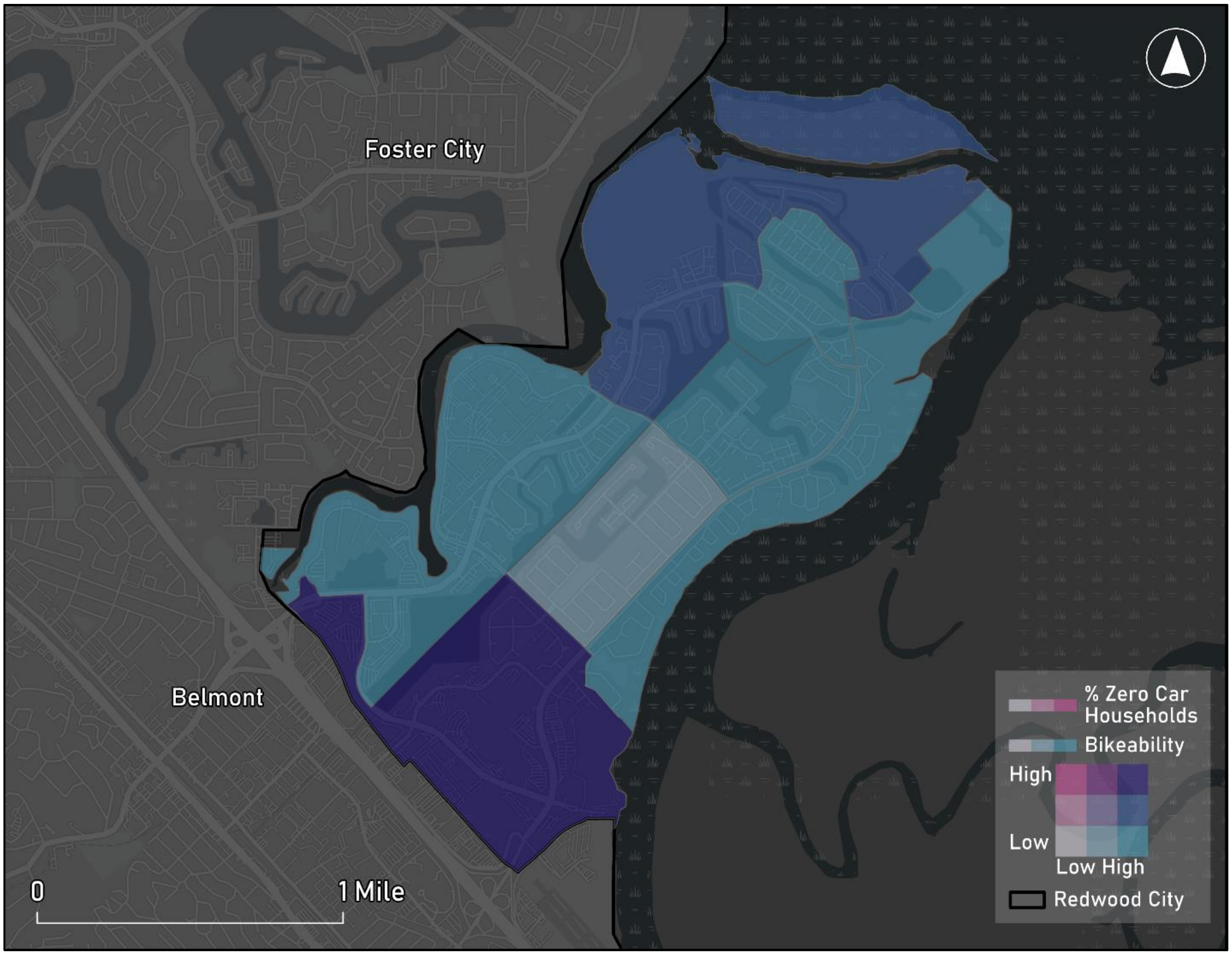


Figure 59. Bikeability and zero car household percentage in Redwood Shores

Redwood Shores residents generally have a moderate to high median household income, aside from the furthest south block group (Figure 60).

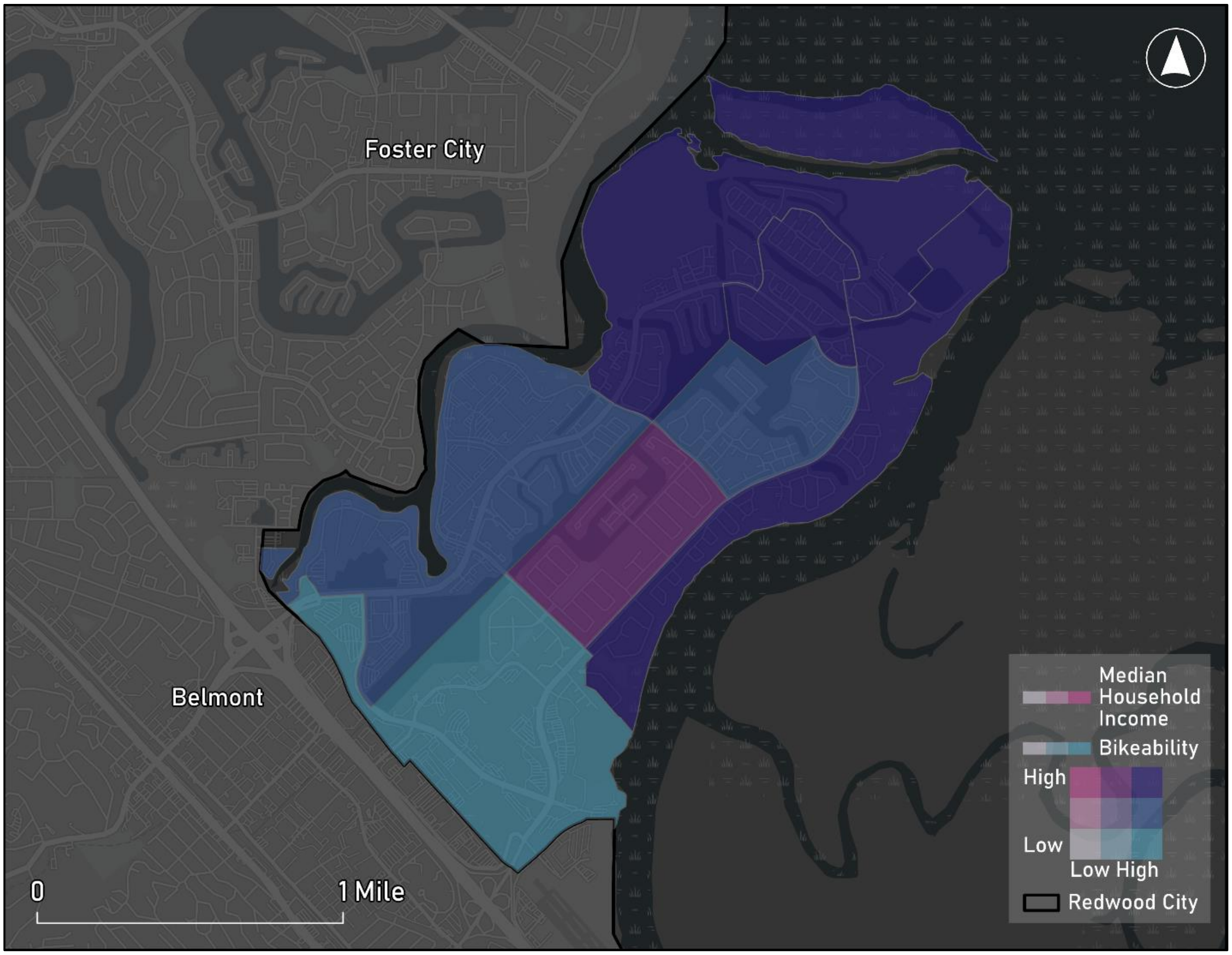


Figure 60. Bikeability and median household income in Redwood Shores

Redwood Shores generally has a moderate to high non-white percentage, with the highest non-white percentages being located in the block groups that line the southeastern edge of the community (Figure 61).

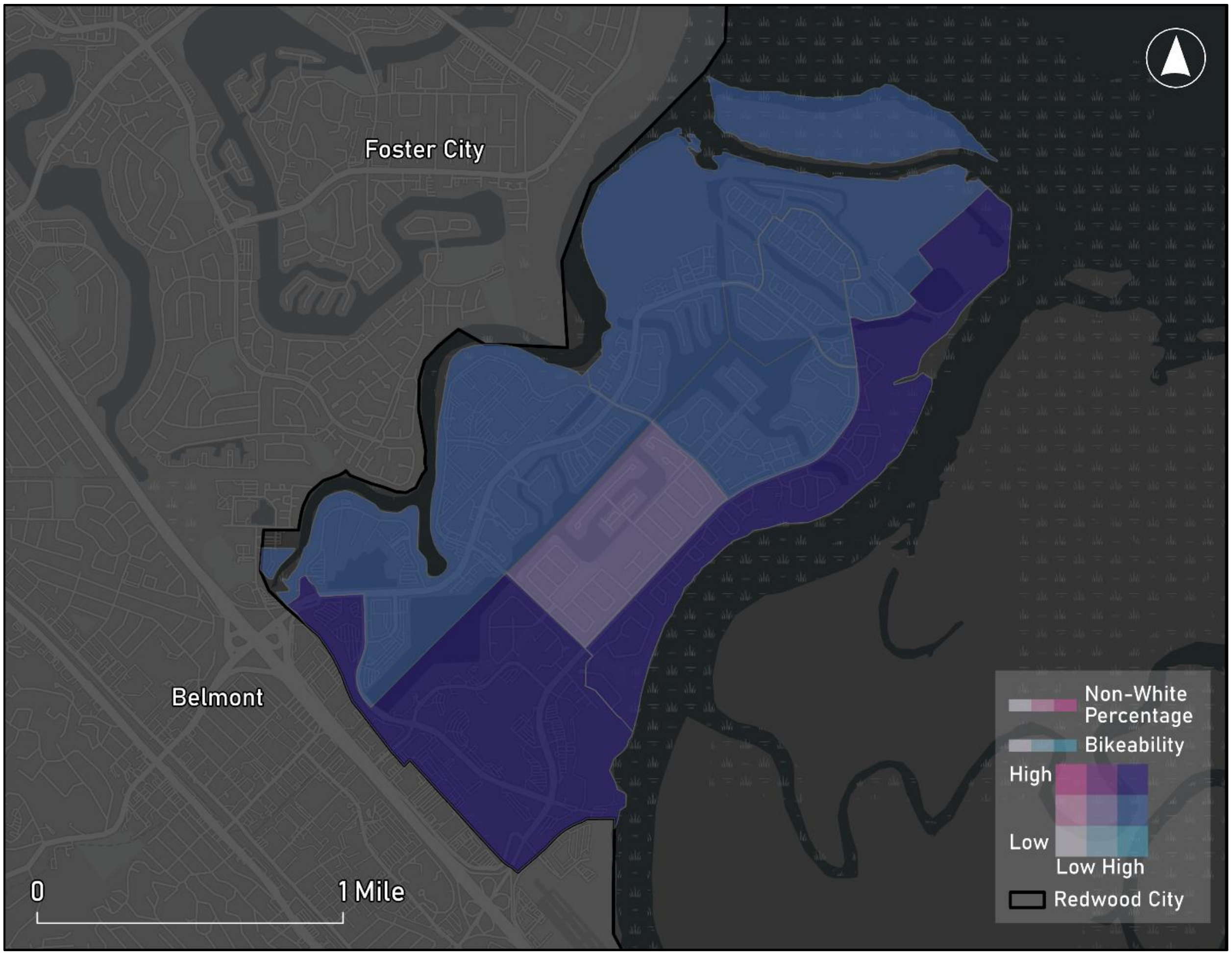


Figure 61. Bikeability and non-white percentage in Redwood Shores

The high bikeability of Redwood Shores makes sense given the appearance of the two highest-weighted variables within the community: bike lane access and slope. Redwood Shores features significant Class I bike infrastructure which greatly improves the overall bikeability of the community's streets. Redwood Shores is also flat, meaning that hilly terrain is a non-issue for local cyclists.

5.4 Site Selection

Each proposed project was assigned a score for bikeability, public opinion, and equity impact. These three scores were then merged in a weighted sum, resulting in a final total score for each proposed project. This total score was used to rank projects in terms of implementation priority. Projects that received a higher priority score were located on a road that as of 2022 had poor bikeability, had strong resident support to be made more bikeable, and was located within neighborhoods that have historically faced inequality in terms of social, economic, and transport resources.

The results of the site selection calculations mirrored what would be expected based on the locations of proposed projects that have a high impact on equity. There is a clear divide, where proposed projects that ranked in the upper 50th percentile of priority are concentrated on the eastern side of the city while proposed projects that ranked in the lower 50th percentile of priority are concentrated on the western side of the city. Furthermore, proposed projects that were mentioned during the workshop that also have a strong impact on equity make up most of the projects between the 75th and 100th percentile. The three highest-scoring projects all either intersected or were directly adjacent to all four of the proposed projects. The relationship between the three proposed projects and the C/CAG Equity Focus Areas (Figure 62, top left), SamTrans Equity Planning Areas (Figure 62, top right), MTC EPCs (Figure 62, bottom left), and CAHPI polygons (Figure 62, bottom right) are visualized in Figure 62.

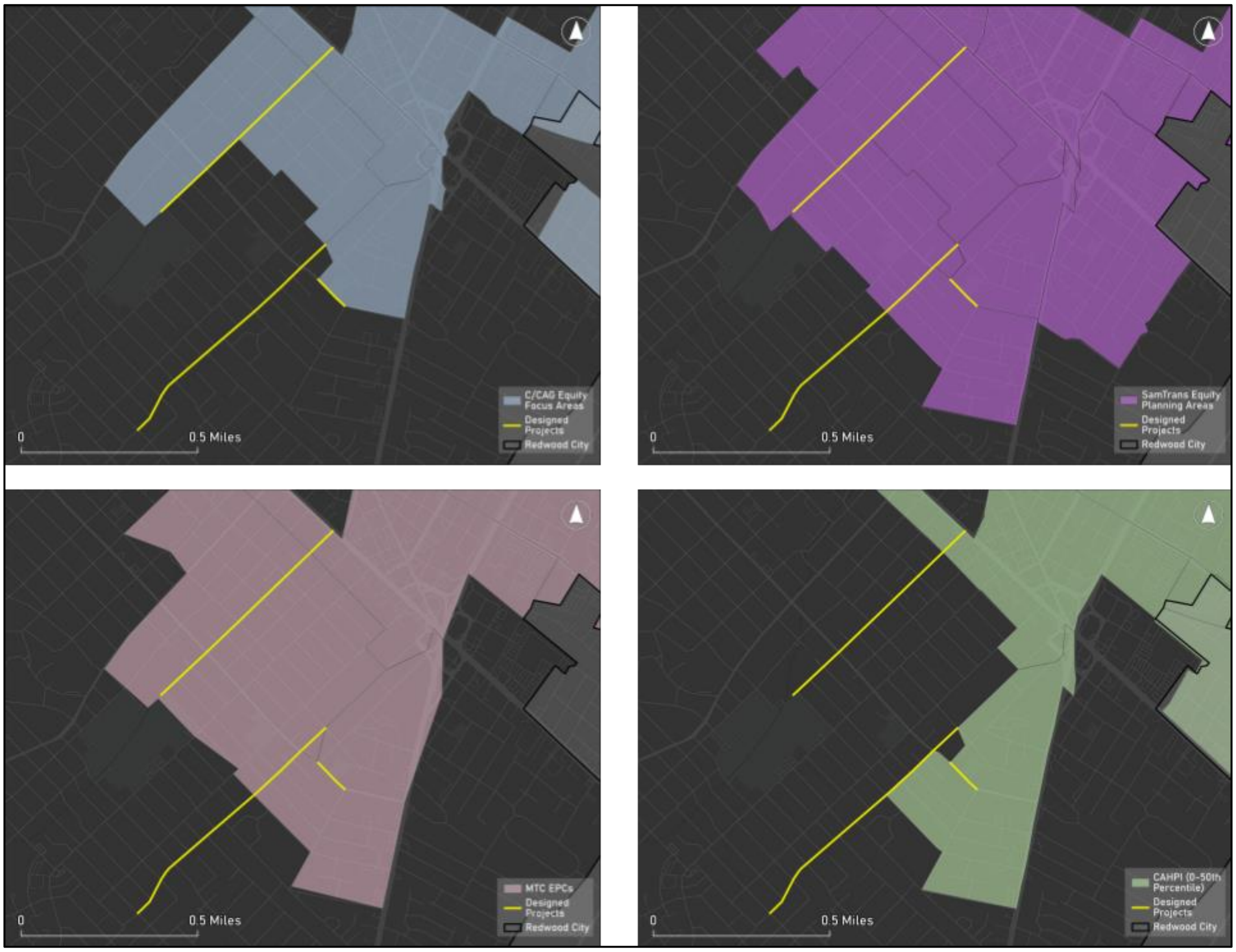


Figure 62. Relationship between the designed projects and equity polygons

The results of the site selection process validate the methodology, because proposed projects which clearly address poor bikeability, inequality, and the needs of residents all scored amongst the highest.

5.5 Urban Design Modeling

Each of the three selected sites underwent a methodical design process, resulting in 3D models and renderings that visualized what improved cycling infrastructure could look like. While the designs may be considered aggressive given the amount of construction they would require, there is precedent for the changes, such as Colorado Avenue in Santa Monica. Additionally, they would most likely significantly increase bicycle ridership given the safety guaranteed by the protected bike lanes. Fully protected bike lanes were selected for all three sites in accordance with the findings of DiGioia (2017), Thomas and DeRobertis (2013), and Standen et al. (2021). All three designs work to improve bikeability, reduce transportation inaccessibility in communities that have been historically underserved, and align with the voiced desires of community members. The final designs accurately portray what the proposed infrastructure could look like in terms of street space allocation, material colors, and a bolstered urban tree canopy.

In addition, all three designs are practical and would increase cycling in the areas surrounding them. Using the fully protected Redwood Avenue cycling infrastructure, parents could escort or send their children to class at Hawes Elementary School on bike before heading to the Roosevelt Center, again on bike, to pick up groceries. They could then cycle to pick up their children and take them to Red Morton Park. This scenario would only require the parents to cycle along seven blocks of unprotected cycling infrastructure throughout their entire day, which minimizes risk and increases cycling rates. Residents living along the new Vera Avenue cycling infrastructure could in theory engage in physical activity or recreation at Red Morton Park, cycle to class, buy groceries, purchase clothing, eat out at a restaurant, and have straightforward access to public transportation without owning a car. Citizens living along Hudson Street would be able to use the new cycling infrastructure to spend an afternoon relaxing at Palm Park, use the gym at the YMCA, or shop along Woodside Road without much worry of being hit by a car, as a result of the fully protected cycling infrastructure.

5.6 Overall Utility of Methods

This project serves as a case study for how a geodesign methodology can be applied to a study area to advance bikeability within that study area. It demonstrates the value in a mixed methods approach and shows that combining techniques from multiple disciplines can have impressive results. Incorporating multiple formats of data can lead to a better-informed decision-making process.

This project ties in methodologies applied in previous bicycle-infrastructure-related studies to produce an interdisciplinary roadmap that can be used to evaluate the existing state of bicycle infrastructure and strategically and objectively plan out how to make improvements to bicycle infrastructure. Existing literature was used to guide the bikeability quantification (Arellana et al. 2020; Codina et al. 2022; Grigore et al. 2019; Grisé and El-Geneidy 2018; Krenn, Oja, and Titze 2015; Olgun 2020; Porter et al. 2020; Winters et al. 2013) and the workshop planning and application (Arellana et al. 2020; Mueller et al. 2018; Mahyar et al. 2016). In the future, this project can serve as an aggregation of past work while also offering new insights as to how to go about improving the bikeability of a given study area.

However, there are important details to consider before attempting to apply this methodology to a study area. First, relevant data must exist and be publicly available. While the data does not have to be identical to the six variables used in this study, it should still be relevant to bikeability and supported by the body of literature. Assuming spatial data is available, a GIS is required. While ArcGIS Pro was used for this project, free GIS software such as QGIS also exists and could be used. SketchUp Pro was used in this project to create the design mockups, however there is a free version of SketchUp that would still prove useful in creating street designs. In addition, SketchUp offers a one-month free trial for the Pro version, which is an opportunity that can be taken advantage of to conduct a similar design process.

While these software and their tools used in this thesis are not overly-complicated, it is still likely that a spatial scientist or GIS analyst would be required to undertake the project. Fortunately, many cities now employ GIS analysts who would be capable of applying this methodology to their jurisdiction.

Specific aspects of the methodology can also be further investigated to optimize the workflow. For example, an analysis comparing the use of different weights in the bikeability weighted sum analysis could be performed to determine the optimal configuration to assess bikeability. The accuracy and effectiveness of this methodology would undoubtedly improve because of learning experiences if it were applied repeatedly in different geographic environments.

Overall, geodesign methodologies are tremendously valuable tools that spark collaboration and innovation and show immense promise as a discipline that can bring about high-quality solutions to pressing humanitarian issues in the built and natural environment, as made evident by this thesis investigation of bikeability in Redwood City.

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