Alternative and Renewable Fuel and Vehicle Technology Program

FINAL PROJECT REPORT

THE 2013 STRATEGIC PLAN FOR THE INAUGURAL ROLLOUT OF HYDROGEN FUELING STATIONS IN CALIFORNIA

Prepared for: California Energy Commission

Prepared by: Advanced Power and Energy Program

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NOTE: The information contained herein was effective October 2013 and served to establish the inaugural strategy for hydrogen station rollout. Subsequent to this date, the information (for example, boundaries, tables, station names, capacities, and addresses) may have been adjusted during implementation.

PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVT Program). The statute, subsequently amended by Assembly Bill 109 (Núñez Chapter 313, Statutes of 2008), authorizes the California Energy Commission to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. The Energy Commission has an annual program budget of about $100 million and provides financial support for projects that:

- Develop and improve alternative and renewable low-carbon fuels.
- Enhance alternative and renewable fuels for existing and developing engine technologies.
- Produce alternative and renewable low-carbon fuels in California.
- Decrease, on a full-fuel-cycle basis, the overall impact and carbon footprint of alternative and renewable fuels and increase sustainability.
- Expand fuel infrastructure, fueling stations, and equipment.
- Improve light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets.
- Expand infrastructure connected with existing fleets, public transit, and transportation corridors.
- Establish workforce training programs, conduct public education and promotion, and create technology centers.

The Energy Commission entered into Interagency Agreement ARV 600-10-002 with the University of California at Irvine to provide funding under the ARFVT Program to enhance the Spatially and Temporally Resolved Energy and Environment Tool (STREET). To be eligible for funding under Agreement ARV 600-10-002, the project must also be consistent with the Energy Commission's *ARFVT Program Investment Plan,* updated annually. The agreement ARV-600-10-002 was executed on June 1, 2011.

ABSTRACT

A comprehensive network of hydrogen fueling stations is required to enable an early market of commercial fuel cell electric vehicles in California. The hydrogen station network will need to minimize upfront equipment capital and target investments to ensure that investments are effectively and efficiently used. These efforts require advanced planning and coordination with stakeholders.

The “Spatially and Temporally Resolved Energy and Environment Tool (STREET),” developed by the Advanced Power and Energy Program at the University of California, Irvine, serves this advanced planning and coordination role through the capability to optimize the number and location of alternative fueling stations based on the intersection of multiple land-use, demographic, traffic pattern, and infrastructure data. STREET has been used in collaboration with stakeholders to support the California Fuel Cell Partnership’s *Strategic Plan for the Rollout of Hydrogen Fueling Stations in California*, the goal of which is to enable the introduction of commercial volumes of fuel cell electric vehicles in the State.

The STREET method and results are described in this report. The results establish (1) that 68 strategically located hydrogen fueling stations (50 new hydrogen fueling stations in addition to the 18 existing or planned stations) are needed in the California by 2015 to enable the introduction of commercial volumes of fuel cell electric vehicles, and (2) the geographic distribution of stations that is required to fuel these vehicles.

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EXECUTIVE SUMMARY

Successful introduction and commercialization of fuel cell electric vehicles in California will require a comprehensive network of hydrogen fueling stations that is adequate to create the level of consumer confidence essential for enabling an early market. With multiple automakers having expressed intent to deploy commercial numbers of fuel cell electric vehicles in 2015, the development of such a network of hydrogen stations is critical. Achieving an adequate network of hydrogen fueling stations is challenging because an insufficient network could impede the market success of fuel cell electric vehicles, while a network that is overbuilt could be exceedingly costly, resulting in longer periods to recuperate investments and demonstrate a successful business case.

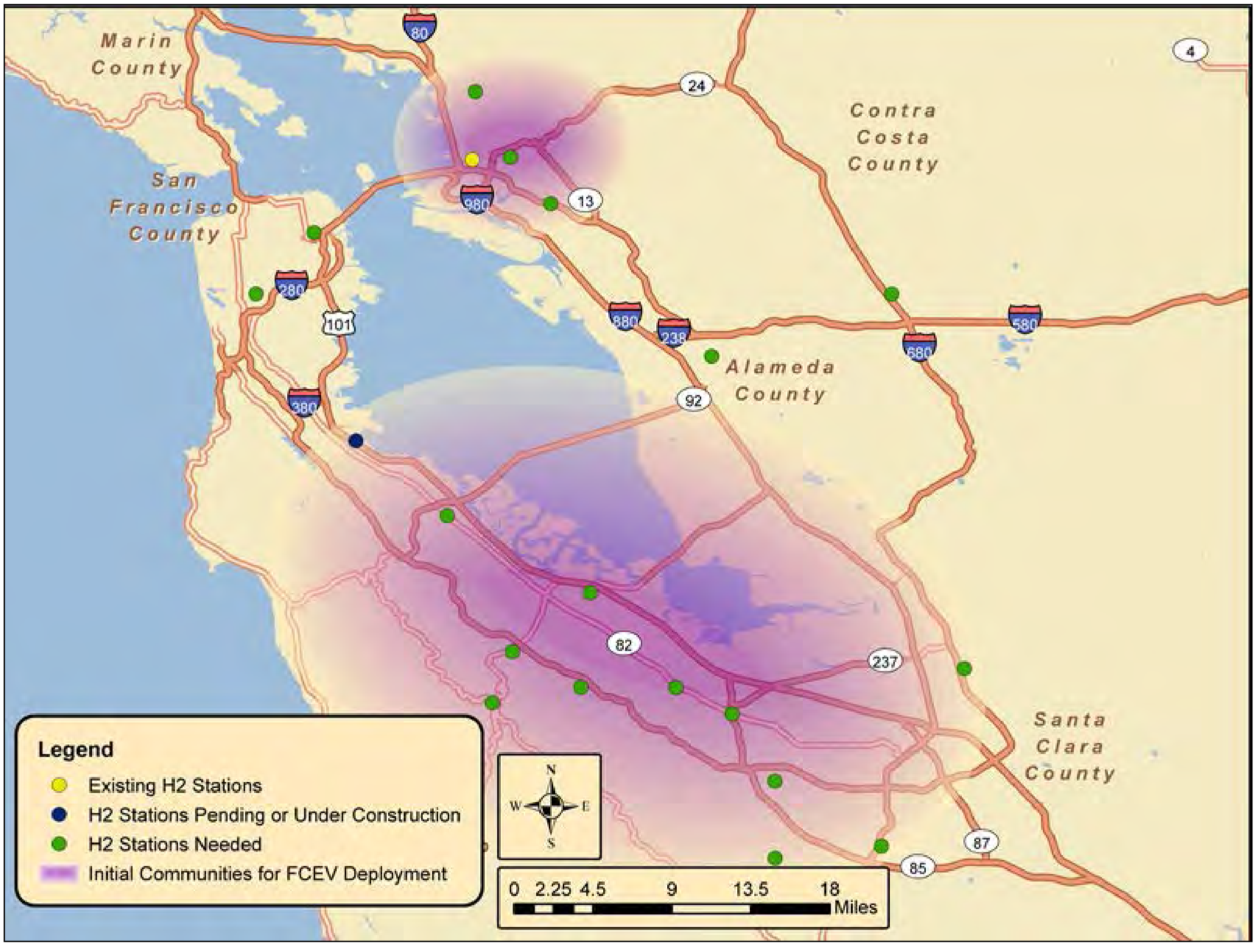
Advanced planning and coordination with stakeholders can help determine both the number and location of hydrogen stations required for an optimized, sufficient network, thus minimizing upfront capital and targeting investments to where they will be most effectively used. The Spatially and Temporally Resolved Energy and Environment Tool (STREET), developed by the Advanced Power and Energy Program at the University of California, Irvine, includes the capability to optimize the number and location of alternative fueling stations based on the intersection of multiple land-use, demographic, and infrastructure criteria that can be found in the referenced items 18 and 19 of the Works Cited section. STREET is used in collaboration with automobile manufacturers and contributes to the California Fuel Cell Partnership's *Strategic Plan for the Rollout of Hydrogen Fueling Stations in California* that will enable the introduction of commercial volumes of fuel cell electric vehicles in the state. The method and results are described in this report.

The strategic plan concludes that 68 strategically located hydrogen fueling stations are needed in California (50 new hydrogen fueling stations in addition to the 18 existing or planned stations) by 2015 to enable the introduction of commercial volumes of fuel cell electric vehicles and determines the geographic distribution of stations that are required. The proposed network of 68 stations, strategically located throughout the state, as shown in Figure 1, represents the leanest possible network that provides a minimum threshold of accessibility to early fuel cell electric vehicle customers. Deploying the leanest possible network both minimizes capital investment and maximizes the throughput of hydrogen fuel at each station so that capital investments may be recovered in shorter periods.

Figure 1: Location of 18 Existing and 50 Additional Hydrogen Fueling Stations Required in California by 2015 to Enable Commercial Volumes of Fuel Cell Electric Vehicles Shown for the Entire State

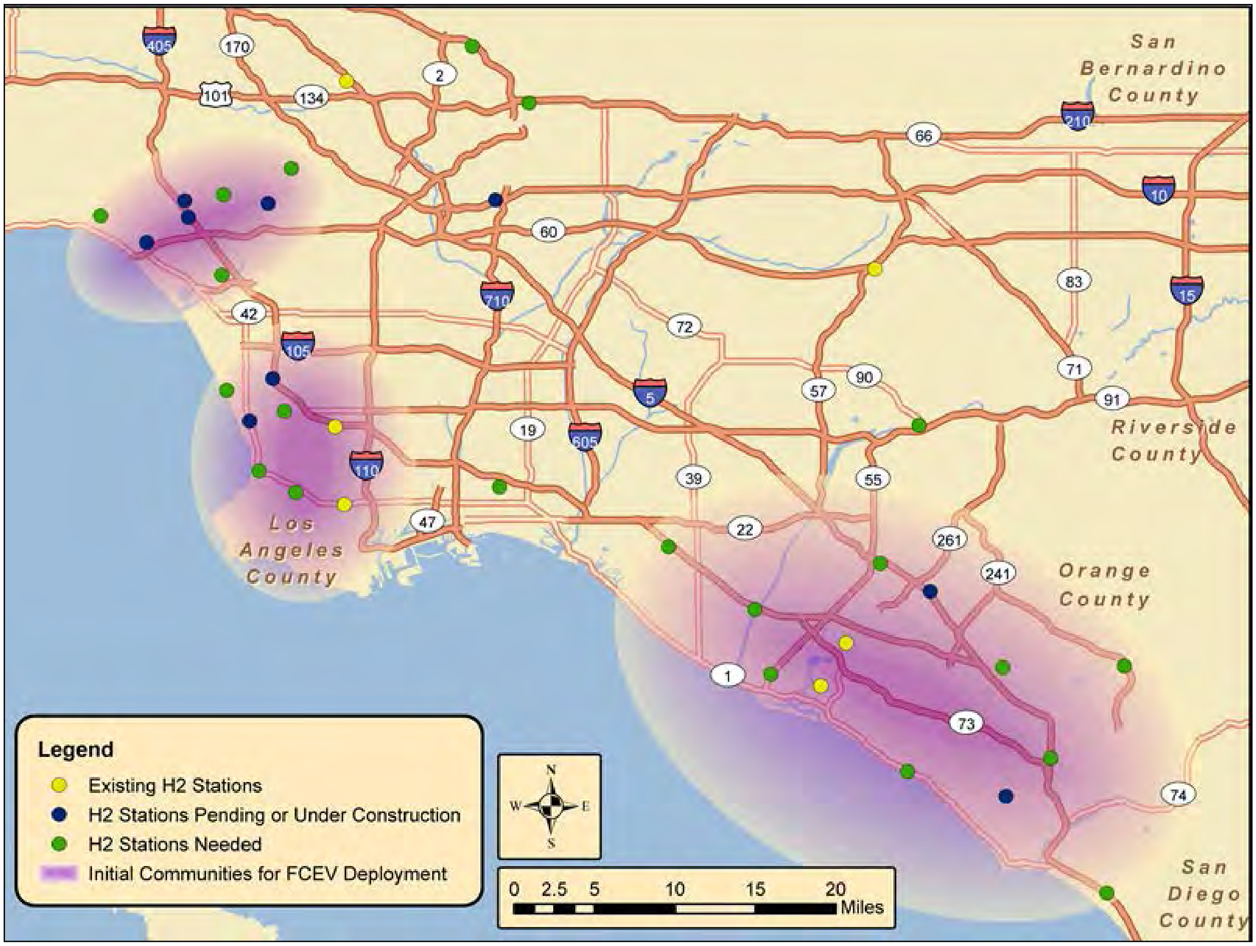
Source: UC Irvine

Figure 2: Location of 18 Existing and 50 Additional Hydrogen Fueling Stations Required in California by 2015 to Enable Commercial Volumes of Fuel Cell Electric Vehicles Shown for the Initial Communities for Fuel Cell Electric Vehicles Deployment in the San Francisco Bay Area



Source: UC Irvine

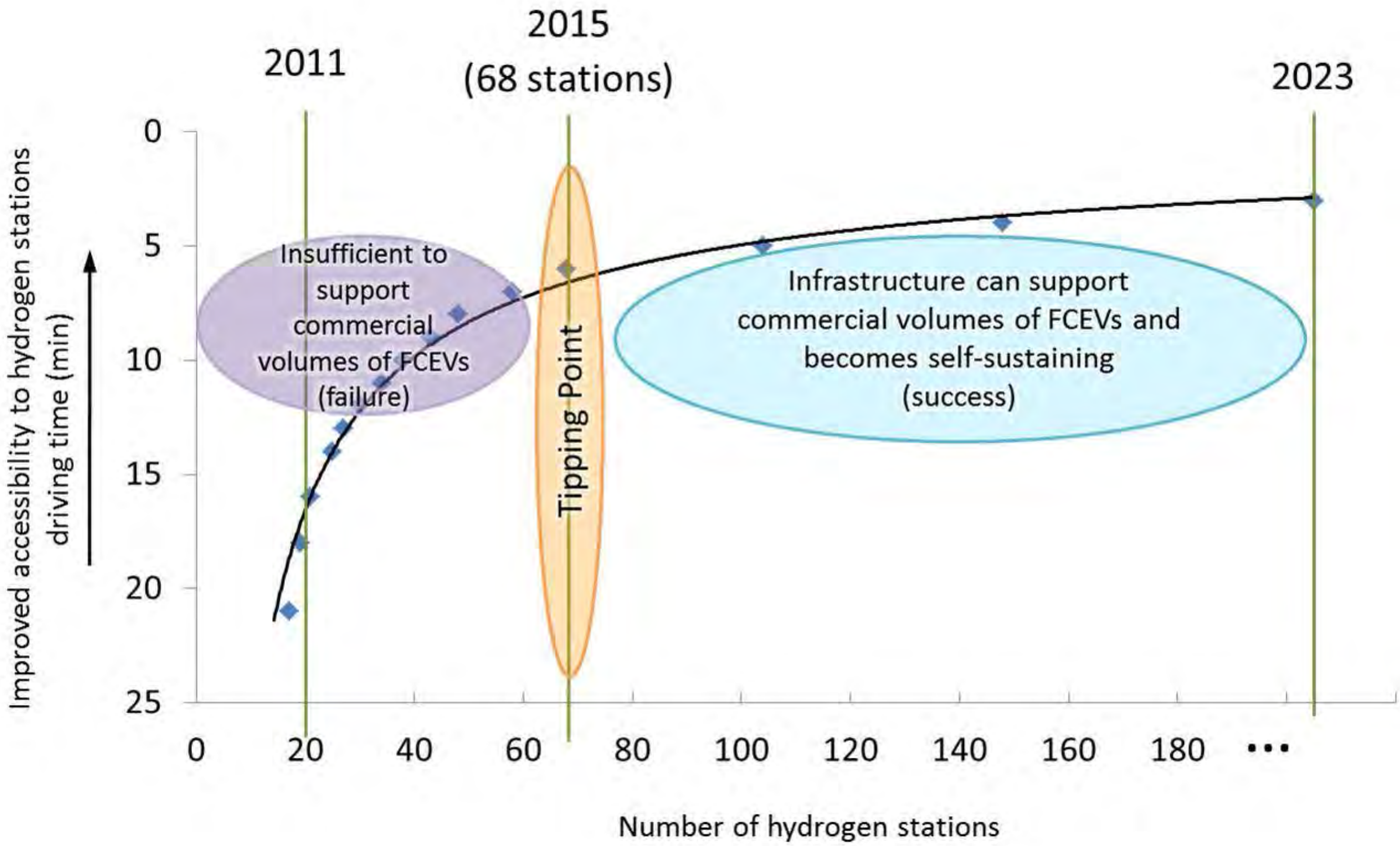
Figure 3: Location of 18 Existing and 50 Additional Hydrogen Fueling Stations Required in California by 2015 to Enable Commercial Volumes of Fuel Cell Electric Vehicles Shown for the Initial Communities for Deployment in the Los Angeles Basin



Source: UC Irvine

Concomitantly, an insufficient network of hydrogen refueling stations (that is, a network that falls short of the 68 stations or neglects to locate the stations in the recommended geographic distribution) will likely impede the market success of fuel cell electric. Furthermore, as shown in the underlying analysis, when the network of hydrogen fueling stations is sparse, additional stations strategically grow the network and result in large improvements to driver accessibility (that is, the amount of time that a fuel cell electric vehicle customer will have to drive to reach a station in terms of minutes). A 68-station network in the state represents a “tipping point” in that a network of fewer than 68 will likely be insufficient to support commercial numbers of fuel cell electric vehicles, and as the network grows beyond 68 stations, it will support commercial volumes of fuel cell electric vehicles and likely become self-sustaining, as shown in Figure 4.

Figure 4: A California Network of 68 Hydrogen Stations Lies at the Tipping Point Between Insufficient Infrastructure and a Self-Sustaining Market



Source: UC Irvine

Two regions in California are identified as targets for fuel cell electric vehicle early commercial markets as a result of a collaborative information exchange and data analysis among automobile manufacturers, researchers at the Advanced Power and Energy Program, and the California Fuel Cell Partnership (CaFCP)

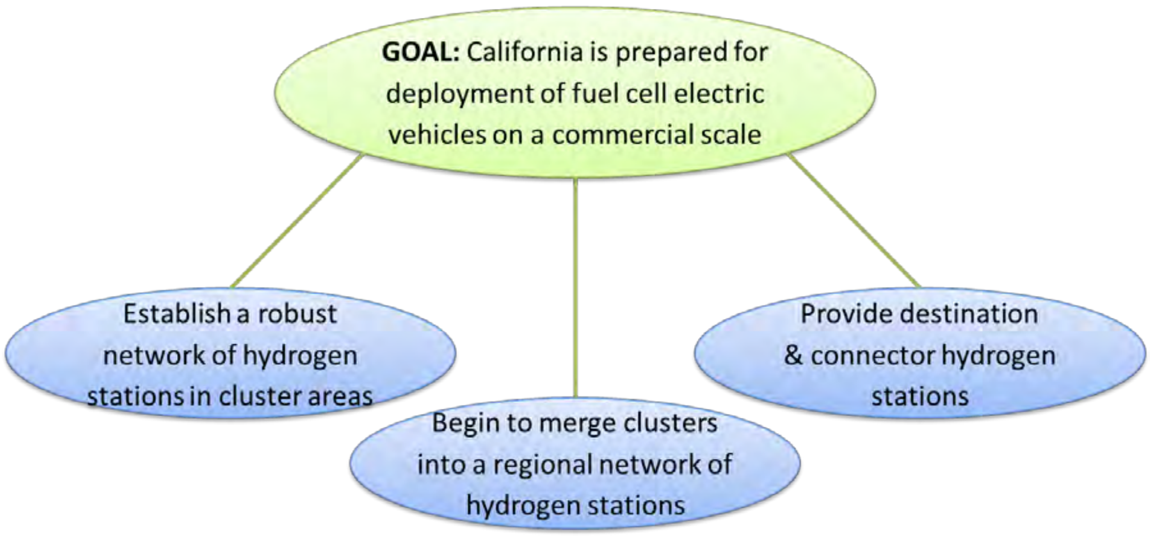
(1) The South Coast of California (primarily Los Angeles and Orange Counties)
(2) The San Francisco Bay Area (primarily San Mateo, Santa Clara, and Alameda Counties)

Method to Determine Hydrogen Stations Needed in California

Researchers at the Advanced Power and Energy Program used STREET while working with automobile manufacturers and the California Fuel Cell Partnership to analyze hydrogen fueling station needs for preparing California for deployment of fuel cell electric vehicles on a commercial scale. The following method is applied to produce the recommendations in the strategic plan.

California will be prepared for deployment of fuel cell electric vehicles on a commercial scale if (1) a robust network of hydrogen stations is established within the "clusters" of each fuel cell electric vehicle target region, (2) additional hydrogen stations within each target region begin to merge the clusters into a regional network of stations, and (3) hydrogen stations are deployed to provide connectivity from a target region to typical destinations, as shown in Figure 5.

Figure 5: Three Infrastructure Requirements for Commercial Fuel Cell Vehicle Deployment



Source: UC Irvine

Robust Network of Hydrogen Stations in Cluster Areas

Within each target region for an early fuel cell electric vehicle market, specific communities where market potential for fuel cell electric vehicles appears to be particularly high (based on automaker market research and Advanced Power and Energy Program data analysis) have been identified and referred to as "clusters." Clusters are summarized in Table 1.

Table 1: Initial Target Regions and Clusters for Fuel Cell Electric Vehicle Commercialization

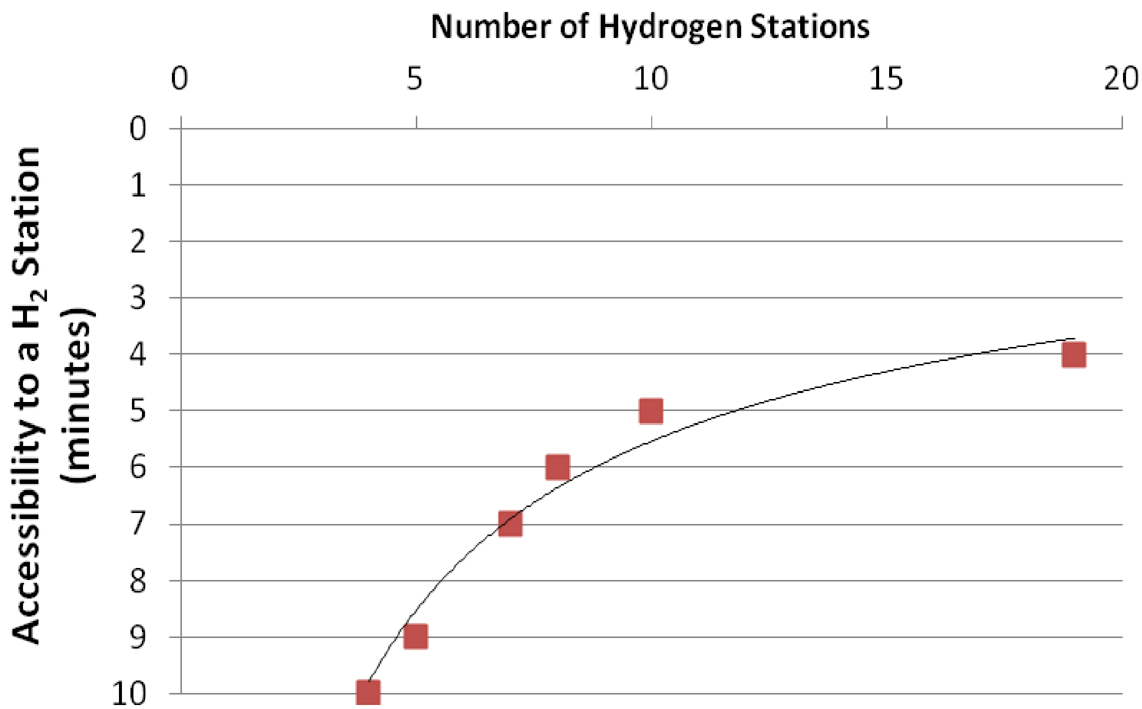
Target Regions for Fuel Cell Electric Vehicle Early Markets	Clusters Within Target Regions
South Coast Air Basin	Santa Monica and West Los Angeles
	Coastal and southern Orange County
	Torrance and nearby coastal cities
San Francisco Bay Area	South Bay Area
	Berkeley

Source: UC Irvine

A *robust network of hydrogen stations within each "cluster"* is defined by the number and location of strategically located hydrogen stations needed to assure that a driver within the cluster can access a station in six minutes of driving or less, equating to the addition of hydrogen at 5-7 percent of existing gasoline stations. These optimized locations are determined by STREET, which employs a set-covering analysis (advanced mathematics involving algorithms) and optimization routine in which the existing road infrastructure is modeled to determine driving times to hydrogen stations within the cluster.

When optimization is assessed at several stages of accessibility within a cluster, it becomes apparent that the strategic placement of each additional hydrogen station improves accessibility by drivers, but at a diminishing rate. Figure 6 demonstrates that initial stations added to the Santa Monica and West Los Angeles cluster create substantial improvements in driving accessibility compared to stations that are added later, in which case modest improvements in driving accessibility can require several stations. (For example, improving driving accessibility from 5 minutes to 4 minutes requires five additional hydrogen stations.) An analysis in each cluster area produced a similar trend as that observed in Figure 6.

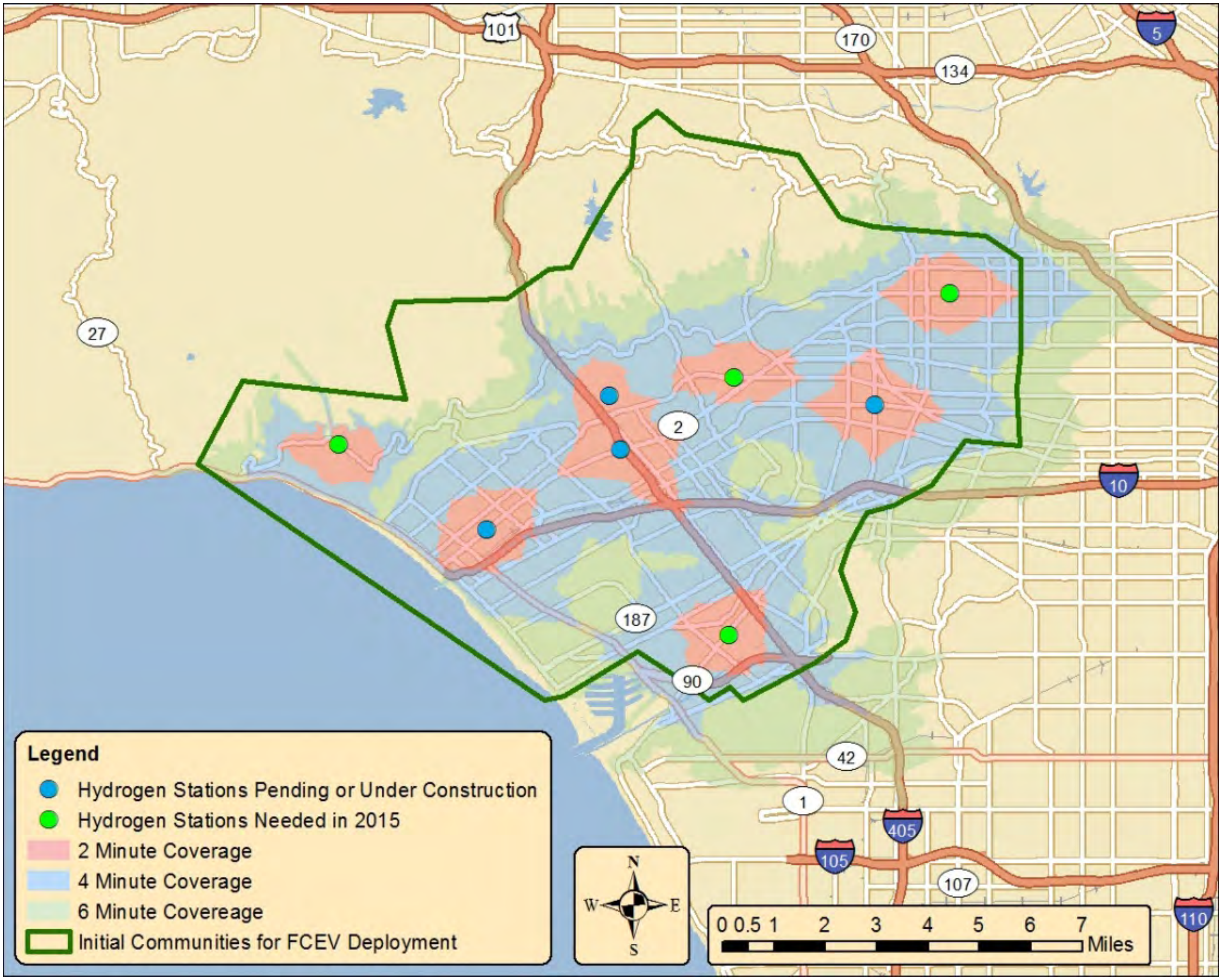
Figure 6: Hydrogen Station Coverage for Fuel Cell Electric Vehicle Customers vs. Number of Hydrogen Stations for the Santa Monica Region



Source: UC Irvine

The selection of a six-minute maximum travel time is based on previous optimization research, driver behavior surveys, and a need to balance network strength with network cost. Current gasoline infrastructure provides access within 4 minutes of driving time or less in all five cluster regions (Figure 6 provides an example for the Santa Monica/West Los Angeles region), and results from the STREET analysis in each of the "clusters" shows that hydrogen dispensing needs to be colocated at only 11 –14 percent of current gasoline stations to provide 4-minute accessibility. However, this is considered overbuilt for the needs of consumers. Previous fuel station siting analyses have concluded that roughly 5 percent of existing gasoline stations need to serve hydrogen to allay drivers' concerns for fuel availability while stating that simply applying a given percentage is inaccurate. Careful optimization, as performed here, is required to produce an adequate network having so few stations. As an example, Figure 7 shows an optimized solution for hydrogen stations in the Santa Monica area with the service coverage that a proposed hydrogen station network provides at 2, 4, and 6 minutes of driving time.

Figure 7: Optimized Solution for Hydrogen Stations in the Santa Monica Region to Guarantee Drivers Access to Hydrogen in 6 Minutes or Less



Source: UC Irvine

Clusters Begin to Merge Into a Regional Network of Hydrogen Stations

Successful deployment of fuel cell electric vehicles on a commercial scale requires that the network of hydrogen stations in each target region expand beyond the confines of the cluster areas. Additional stations that lie outside the clusters can begin merging the clusters into a regional network of hydrogen stations.

Preferred locations for hydrogen stations that merge clusters into a regional network of stations are determined by focusing on residential zones with demographics suggesting strong purchasing power for early commercial fuel cell electric vehicles. Purchasing power is based on median household income, population, and vehicles per household.

Provide Connector and Destination Hydrogen Stations

Through collaboration with automobile manufacturers, provision of accessibility to certain destinations was identified as a critical step toward establishing an early market for fuel cell electric vehicles in California. Some destinations require a hydrogen fueling station only at the arrival point (for example, Palm Springs from the Los Angeles region) and are referred to as "destination stations." Most of the cities identified for "destination stations" have populations and demographic characteristics that suggest they are likely to develop as early markets areas for fuel cell electric vehicles (for example, Santa Barbara, Palm Springs) as well. Others require a fueling station at a midpoint as well as at the end point (for example, San Francisco – L.A. corridor).

The final result is a network of 68 hydrogen stations spanning California as shown in Figures 1, 2, and 3 and Table 2.

Table 2: List of Existing, Planned, and Proposed Hydrogen Stations as of March 2012

Region	Existing or Planned H_2 Stations	Additional H_2 Stations Recommended	Total H_2 Stations Recommended
Robust network of hydrogen stations in cluster areas			
Santa Monica/West LA	4	4	8
Torrance	4	4	8
Orange County	4	9	13
Berkeley	1	3	4
South SF Bay	1	11	12
Begin to merge clusters into a regional network of hydrogen stations			
Burbank	1	0	1
San Fernando Valley	0	1	1
Pasadena	0	2	2
Anaheim	0	1	1
Long Beach	0	1	1
Downtown San Francisco	0	2	2
Pleasanton	0	1	1
Hayward	0	1	1
Sacramento	1	1	2
Riverside	0	1	1
Diamond Bar	1	0	1
Los Angeles (CSULA)	1	0	1
Provide destination and connector hydrogen stations			
La Jolla/Del Mar/San Diego	0	2	2
Santa Barbara	0	1	1
Palm Springs	0	1	1
I-5 Corridor	0	1	1
Sonoma	0	1	1
Napa	0	1	1
Lake Tahoe	0	1	1
Total	18	50	68

Source: UC Irvine

CHAPTER 1: Determination of Early Market

Method

The first step in designing and optimizing a hydrogen station network is to determine the regions for the early fuel cell electric vehicle market. Purchasing power is examined as a basis for comparison to determine which regions in California are preferred for initial deployment of fuel cell electric vehicles. The need to cater to early fuel cell electric vehicle customers has been discussed elsewhere. Median household income, average number of vehicles per household, and population are used as representations of purchasing power.

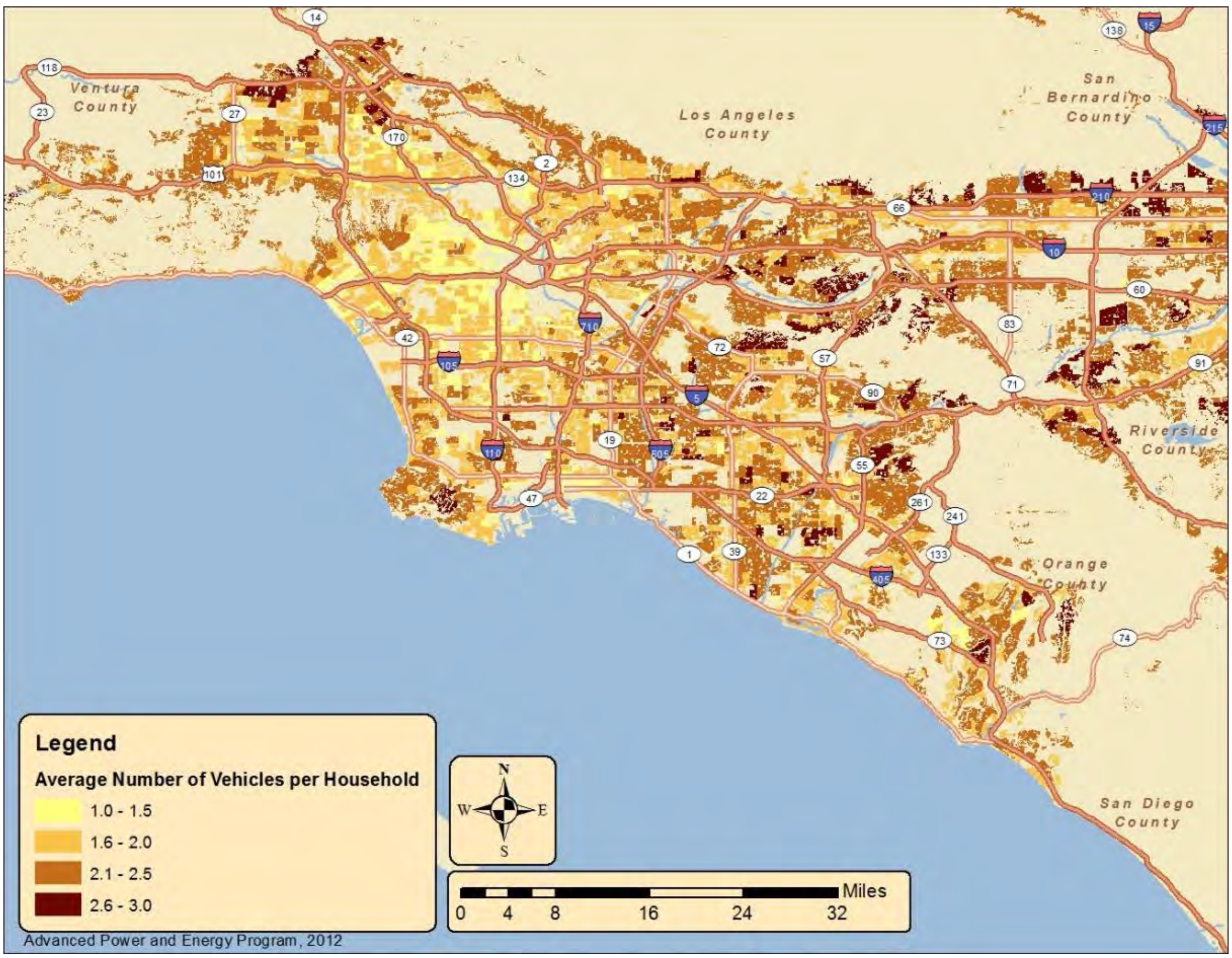
Similar to hybrid vehicles, the first fuel cell electric vehicles that are introduced into the market will be in a higher cost bracket compared to equivalent gasoline vehicles [13]. Therefore, annual median household income is likely the strongest indicator of potential market regions. Figure 8 shows median household income levels for residential areas in the greater Los Angeles region. As shown, high-income households are substantial throughout this area.

Figure 8: Median Household Income Levels by Census Tract [20] for Residential Areas in the Greater Los Angeles Region

Source: UC Irvine

Consumer propensity for vehicle ownership represents a secondary factor determining purchasing power. The range and refueling characteristics of fuel cell electric vehicles are nearly identical to traditional gasoline vehicles, differentiating them from many other alternative vehicles. Therefore, fuel cell electric vehicles can likely serve as the sole vehicle for an individual or household, much as gasoline vehicles often do today. However, early consumers may be more likely to opt for an advanced technology vehicle as their second vehicle rather than as their only vehicle. Furthermore, there are several dense urban areas throughout the United States where public transportation is widely used, enabling many people to successfully commute without owning any vehicle. Figure 9 shows the average number of vehicles per household in the greater Los Angeles region.

Figure 9: Average Number of Vehicles per Household by Census Tract [20] for Residential Areas in the Greater Los Angeles Region



Source: UC Irvine

The number of potential fuel cell electric vehicle buyers is clearly an important factor in the number of cars sold. Figure 10 shows the population density for residential areas in the Los Angeles region.

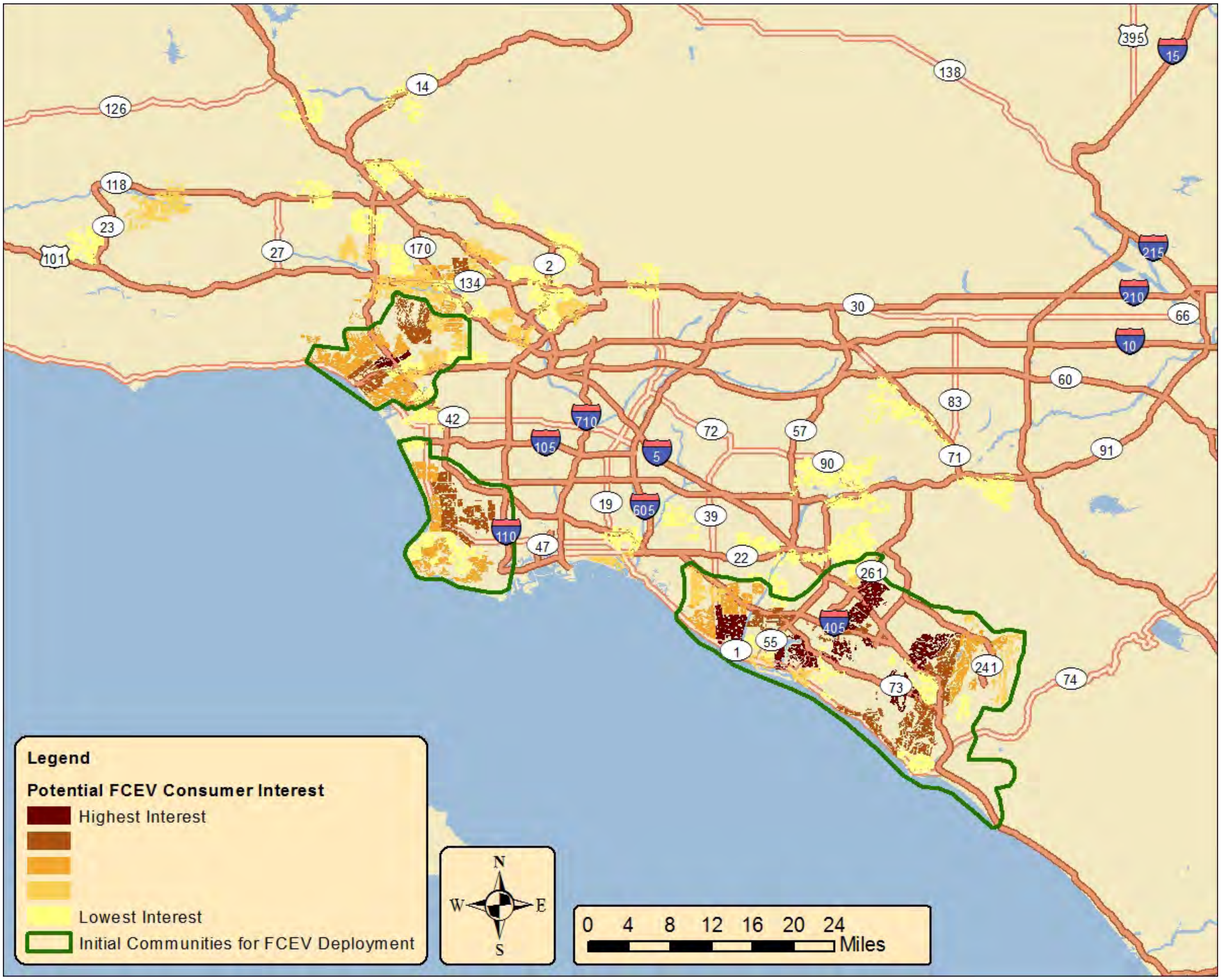
Figure 10: Population Density by Census Tract [20] for Residential Areas in the Greater Los Angeles Region

Source: UC Irvine

Initial Market Regions

Three broad, initial market regions were selected in Southern California based on the combination of household income, population density, and number of vehicles encompassing Santa Monica, Torrance, and much of Orange County, as shown by the green outlined polygons in Figure 11. As drawn, these regions alone are home to more than 3.1 million people, more than 630 gasoline stations, more than 2 million light-duty vehicles, and nearly 200,000 new car sales per year.

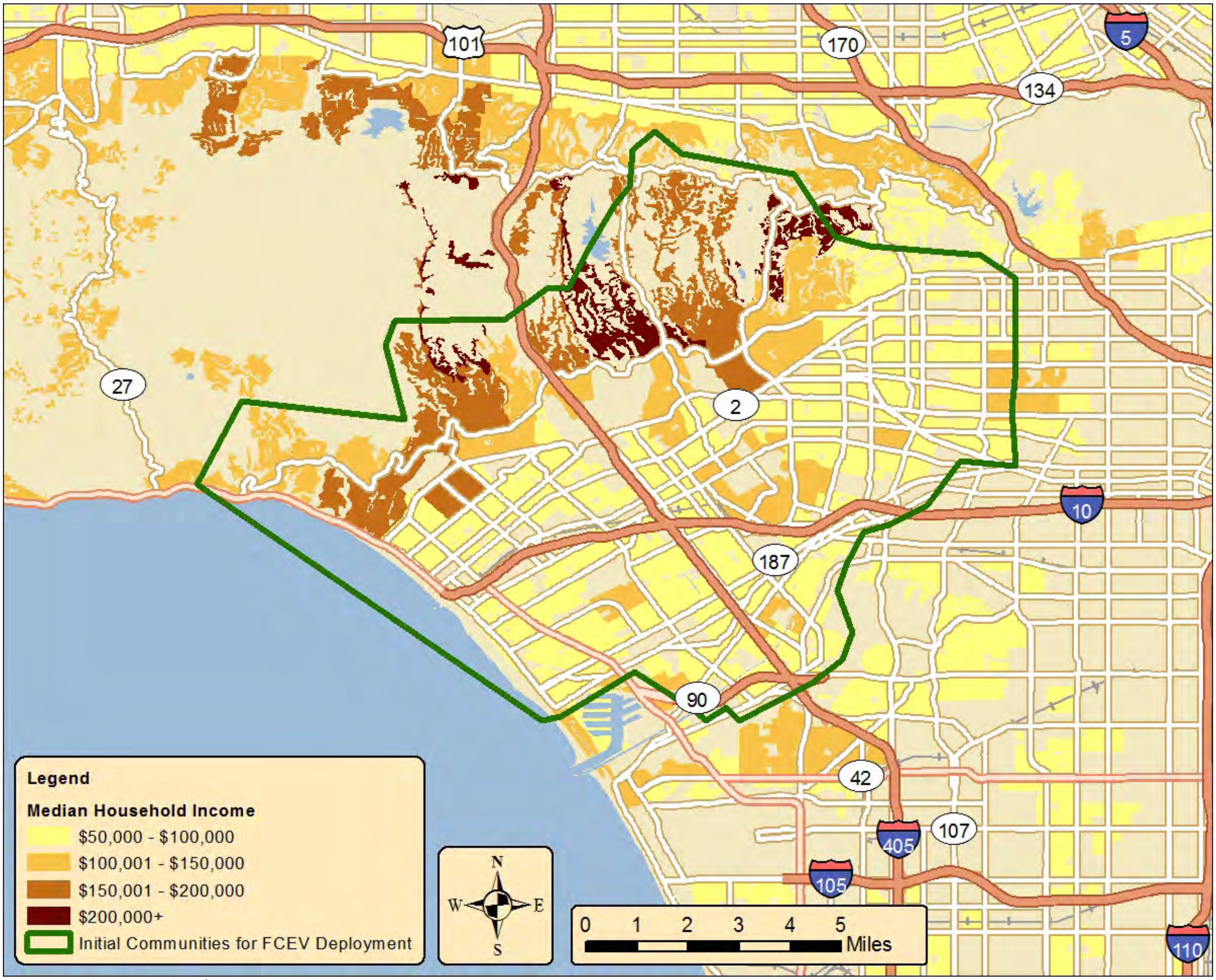
Figure 11: The Three Initial Market Regions in the Los Angeles Basin Overlaid With Automaker Market Information for Potential Customer Interest in Fuel Cell Electric Vehicles



Source: UC Irvine

The Santa Monica region contains 317,150 households and a total population around 669,750. Within this region, 78,298 households report annual incomes greater than $125,000. Figure 12 shows the median household income for this region. Figure 13 shows a similar map for number of vehicles per household. Not coincidentally, many of the areas with high incomes also have more vehicles. 138,789 households possess two or more vehicles.

Figure 12: Gradient Showing Median Annual Household Income by Census Tract [20] for Residential Areas in the Santa Monica Region

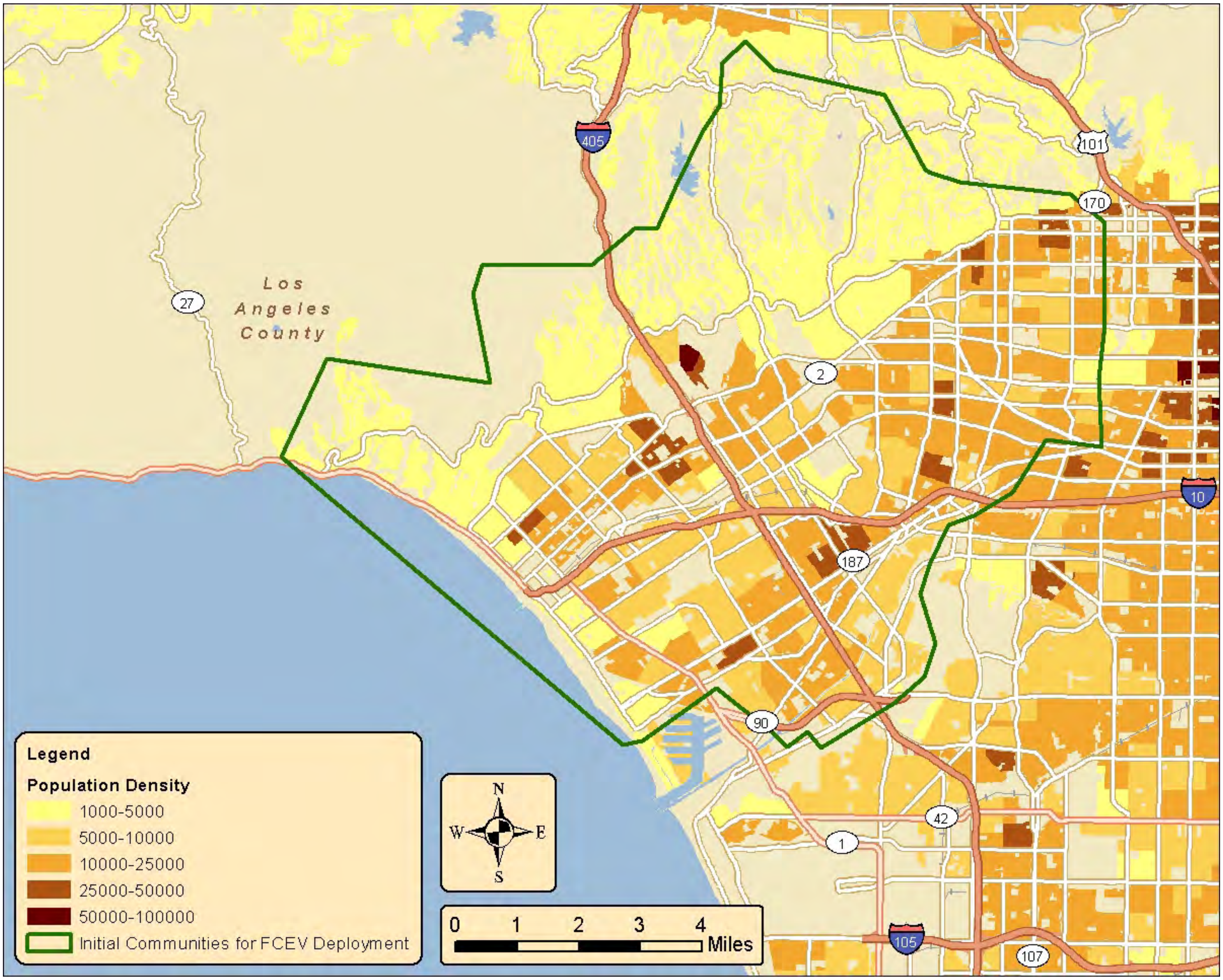


Source: UC Irvine

Figure 13: Gradient Showing Average Number of Vehicles per Household by Census Tract [20] for Residential Areas in the Santa Monica Region

Source: UC Irvine

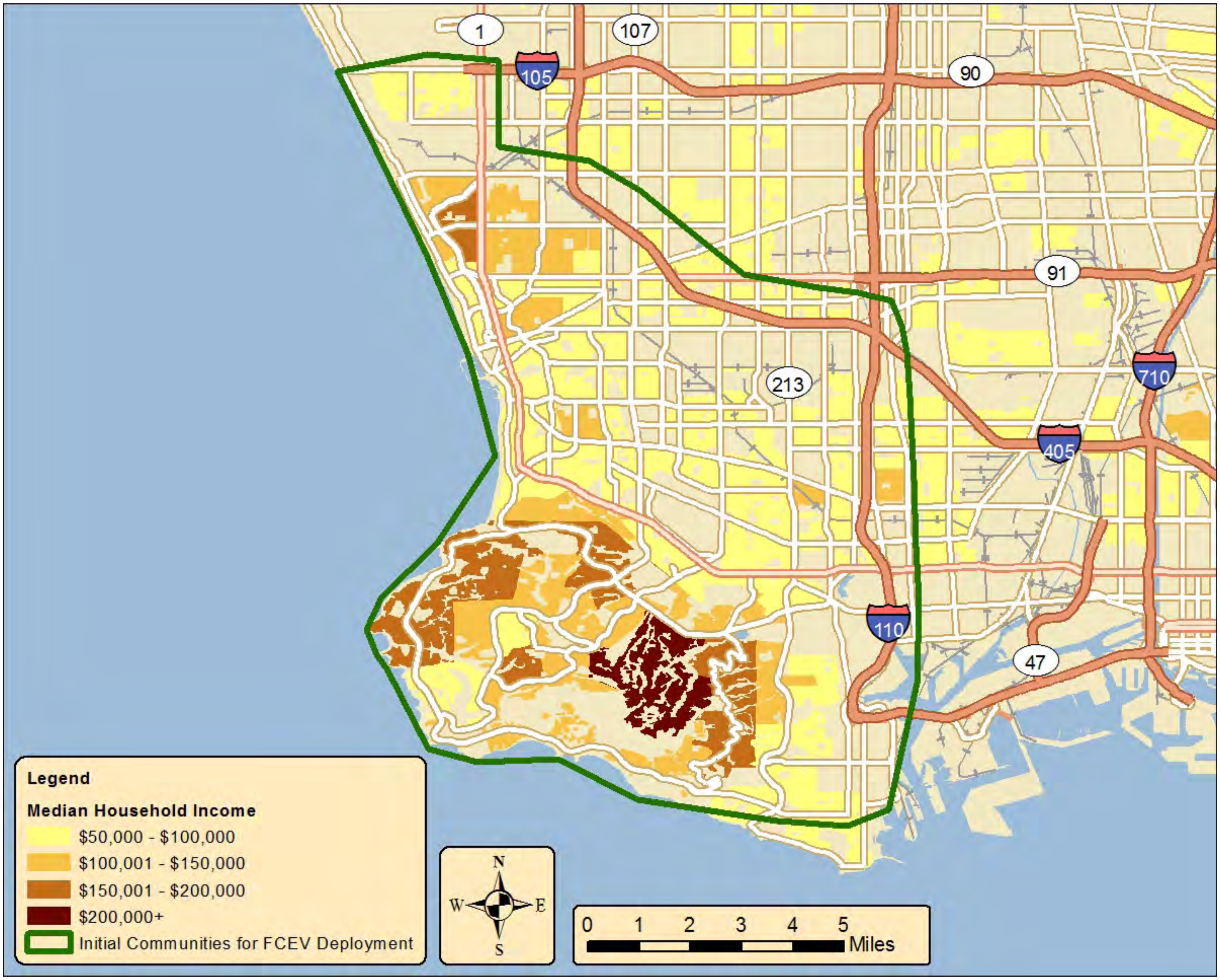
Figure 14: Gradient Showing Population Density by Census Tract [20] for Residential Areas in the Santa Monica Region



Source: UC Irvine

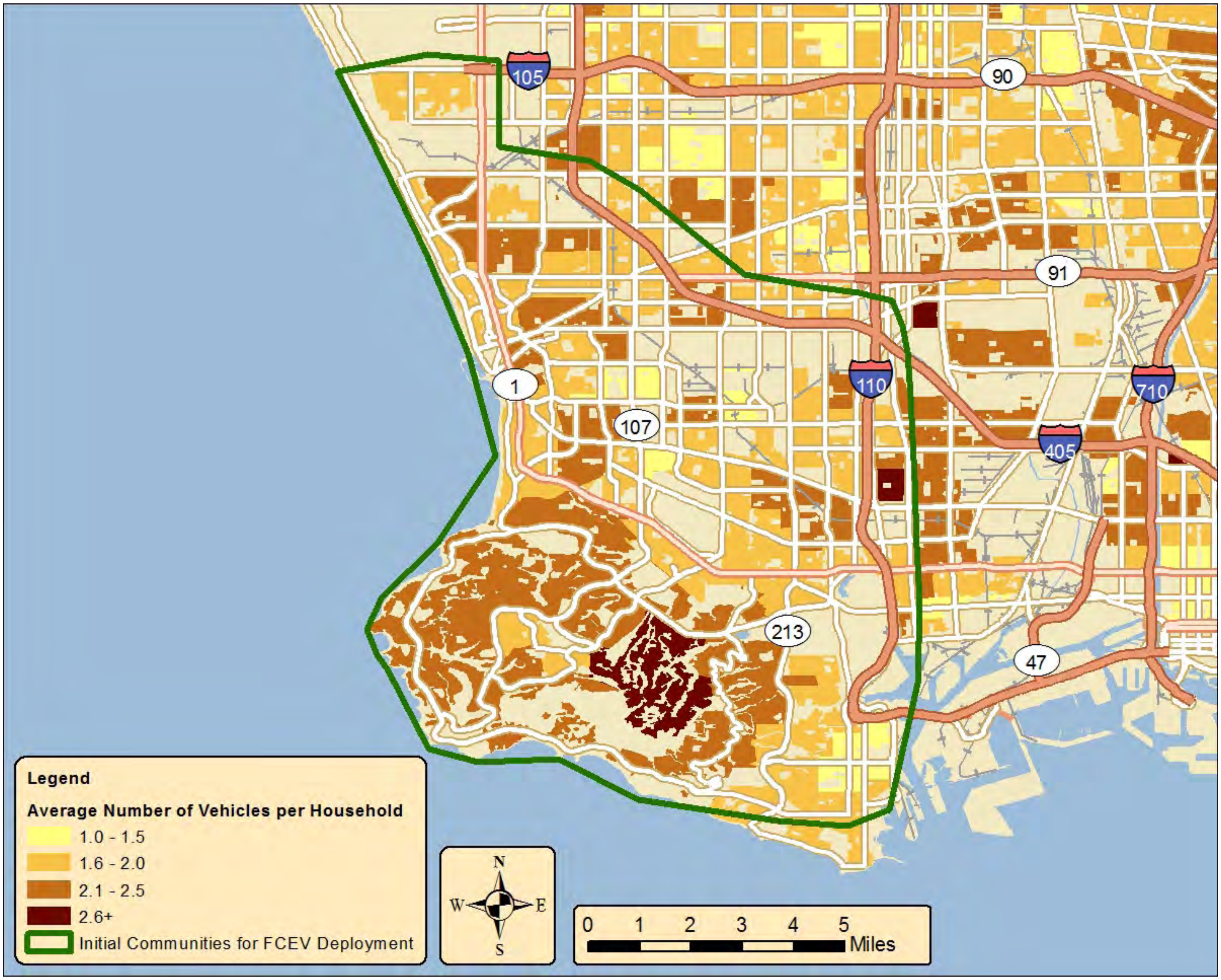
The Torrance region has a total population of approximately 547,845 people living in about 204,630 households. Within this region, nearly 55,730 households report annual incomes greater than $125,000. Figure 15 shows the median household income for this region. Figure 16 shows a similar map for number of vehicles per household. Figure 17 provides information on population. Again, many of the areas with high incomes also have more vehicles. 128,374 households possess two or more vehicles.

Figure 15: Gradient Showing Median Annual Household Income by Census Tract [20] for Residential Areas in the Torrance Region



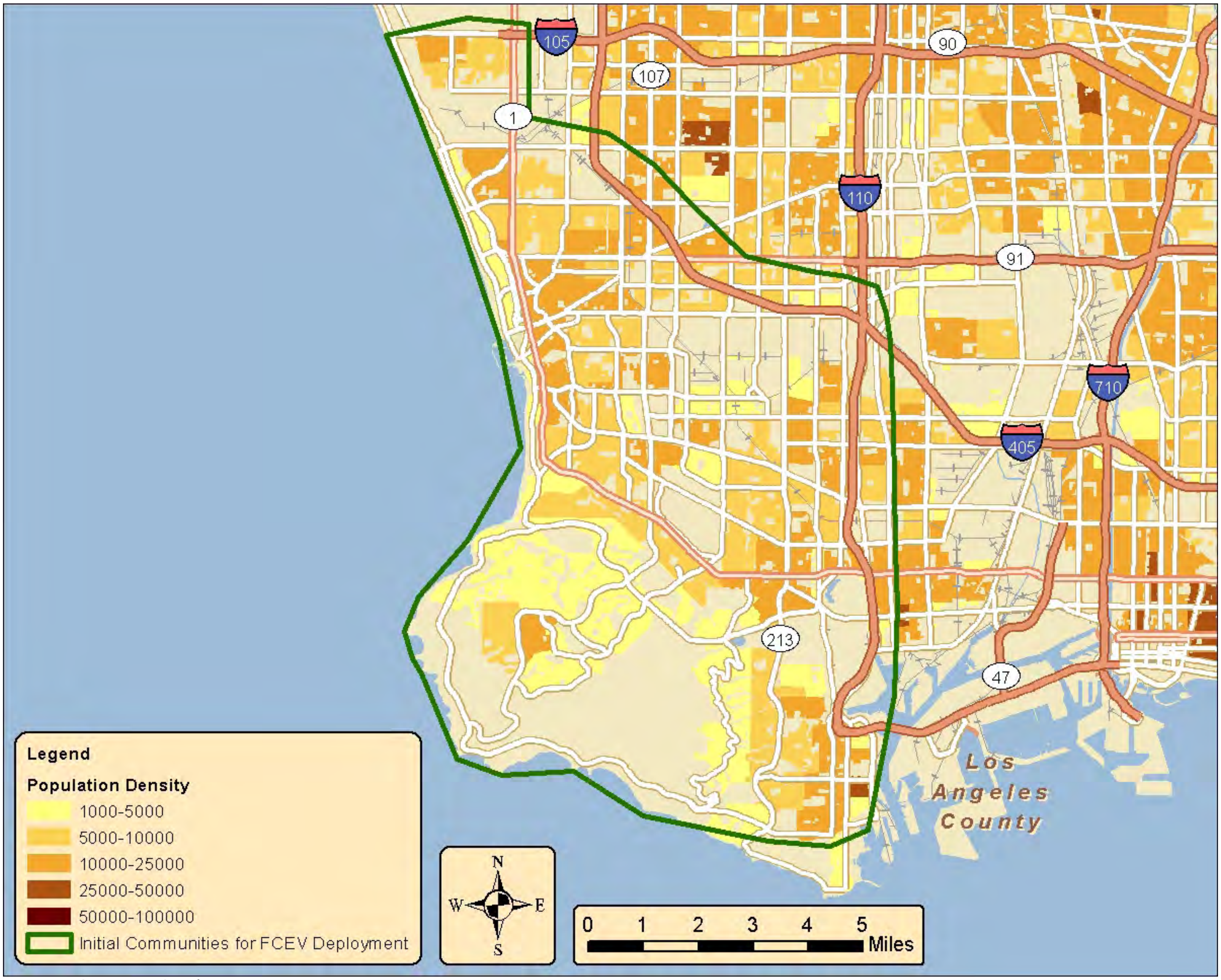
Source: UC Irvine

Figure 16: Gradient Showing Average Number of Vehicles per Household by Census Tract [20] for Residential Areas in the Torrance Region



Source: UC Irvine

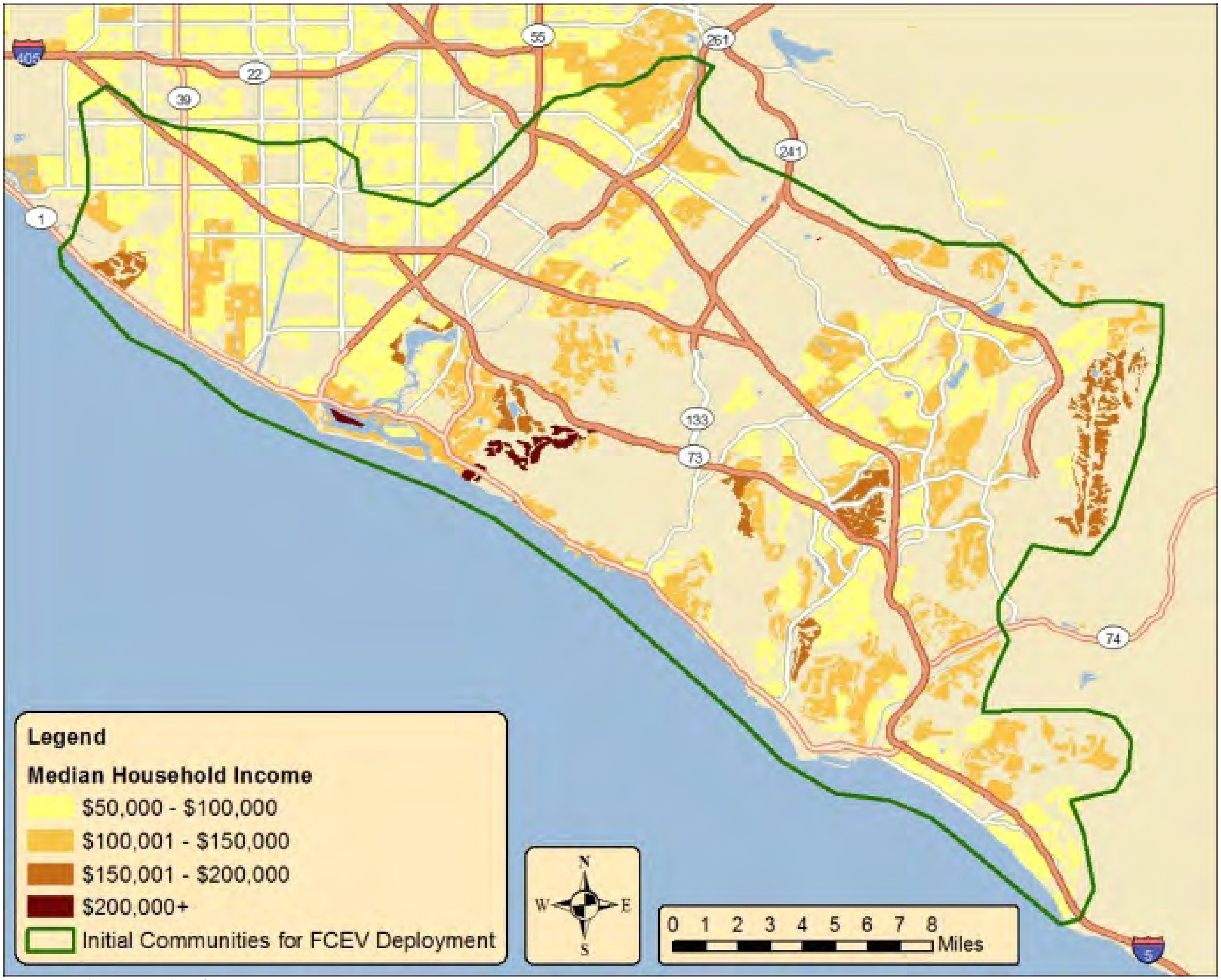
Figure 17: Gradient Showing Population Density by Census Tract [20] for Residential Areas in the Torrance Region



Source: UC Irvine

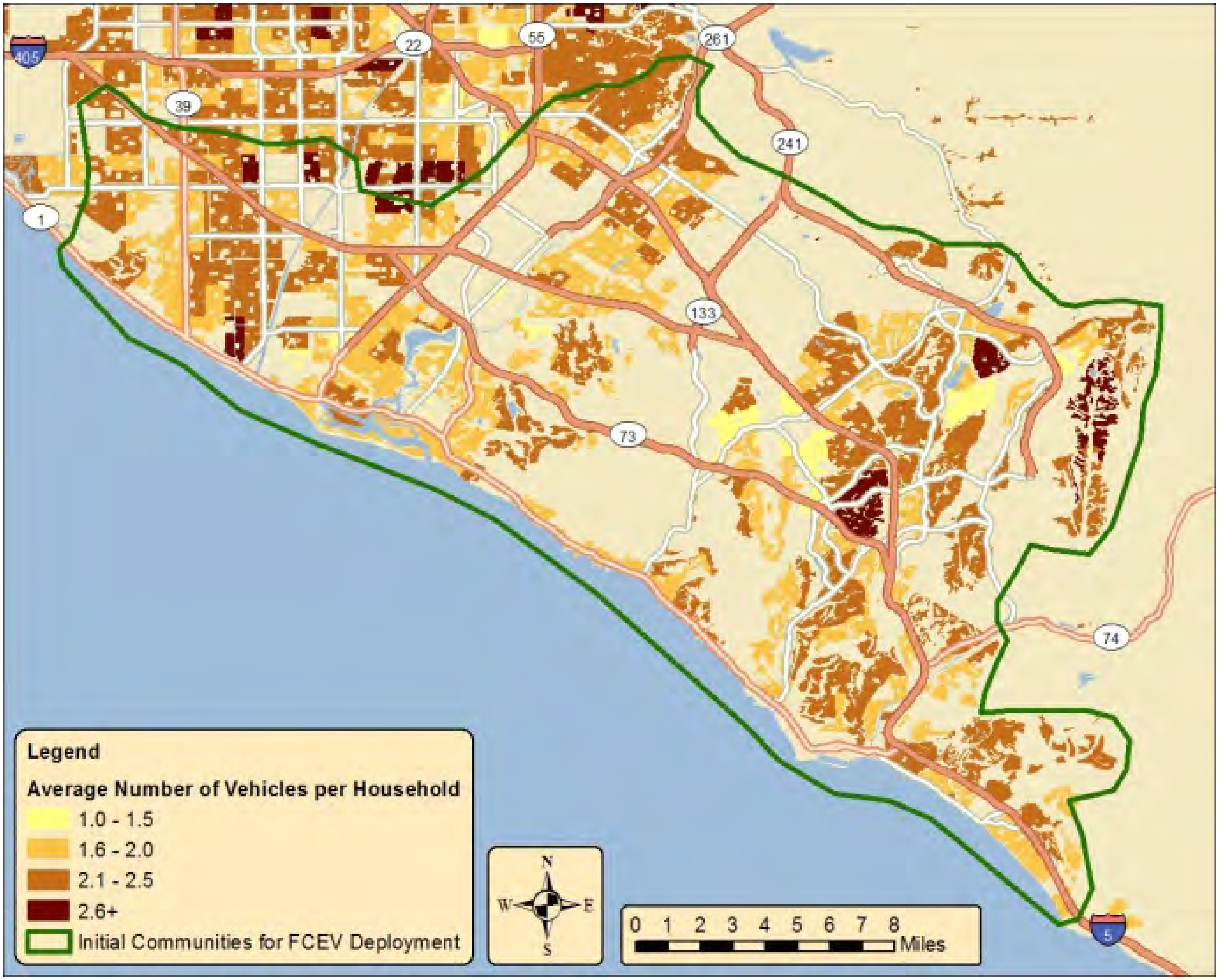
The Orange County region has a total population of approximately 825,900 people living in about 311,500 households. Within this region, 84,980 households report annual incomes greater than $125,000. Figure 18 shows the median household income for this region. Figure 19 shows a similar map for number of vehicles per household. Figure 20 provides population information. Again, many of the areas with high incomes also have more vehicles. 197,262 households possess two or more vehicles.

Figure 18: Gradient Showing Median Annual Household Income by Census Tract [20] for Residential Areas in the Orange County Region



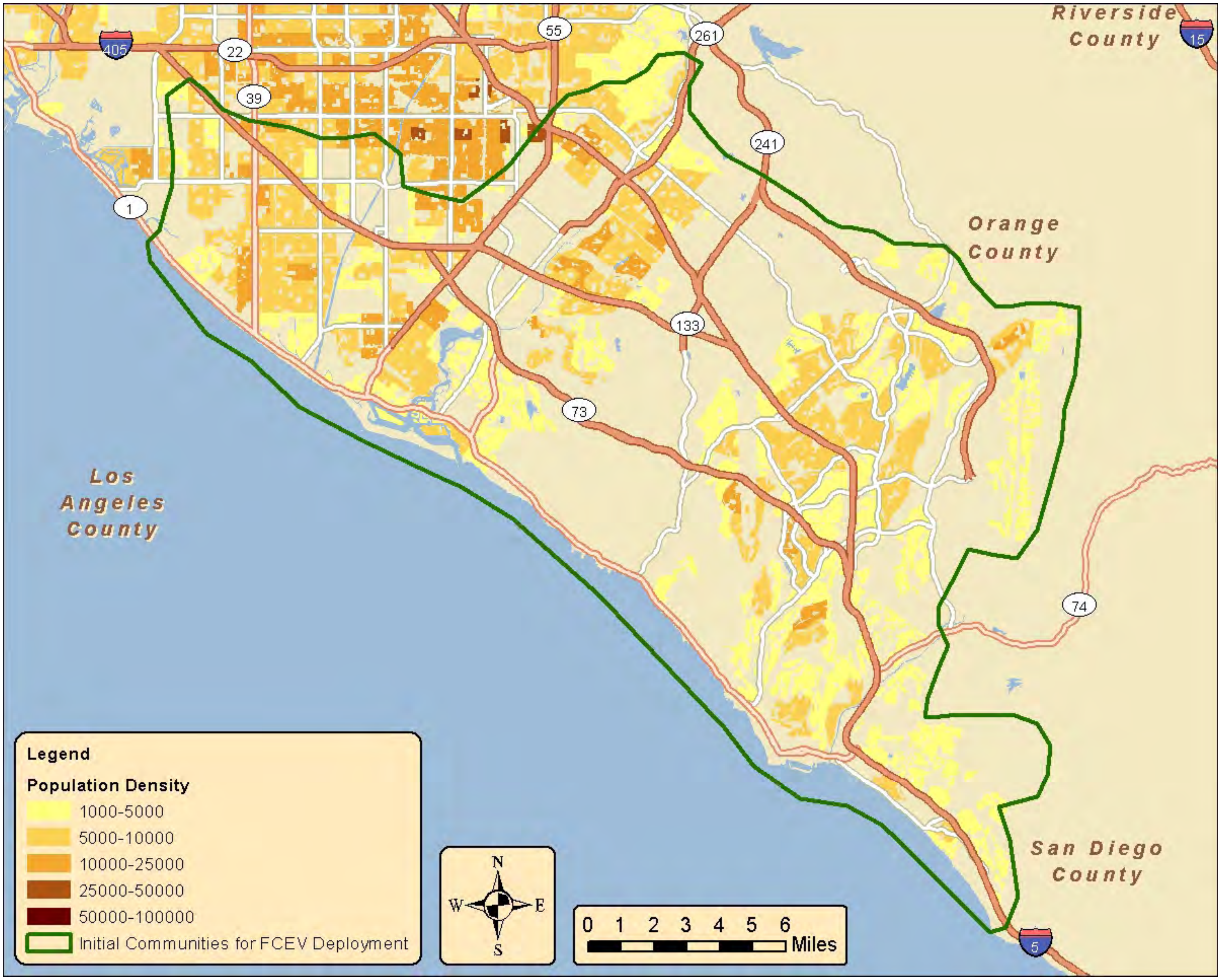
Source: UC Irvine

Figure 19: Gradient Showing Average Number of Vehicles per Household by Census Tract [20] for Residential Areas in the Orange County Region



Source: UC Irvine

Figure 20: Gradient Showing Population Density by Census Tract [20] for Residential Areas in the Orange County Region

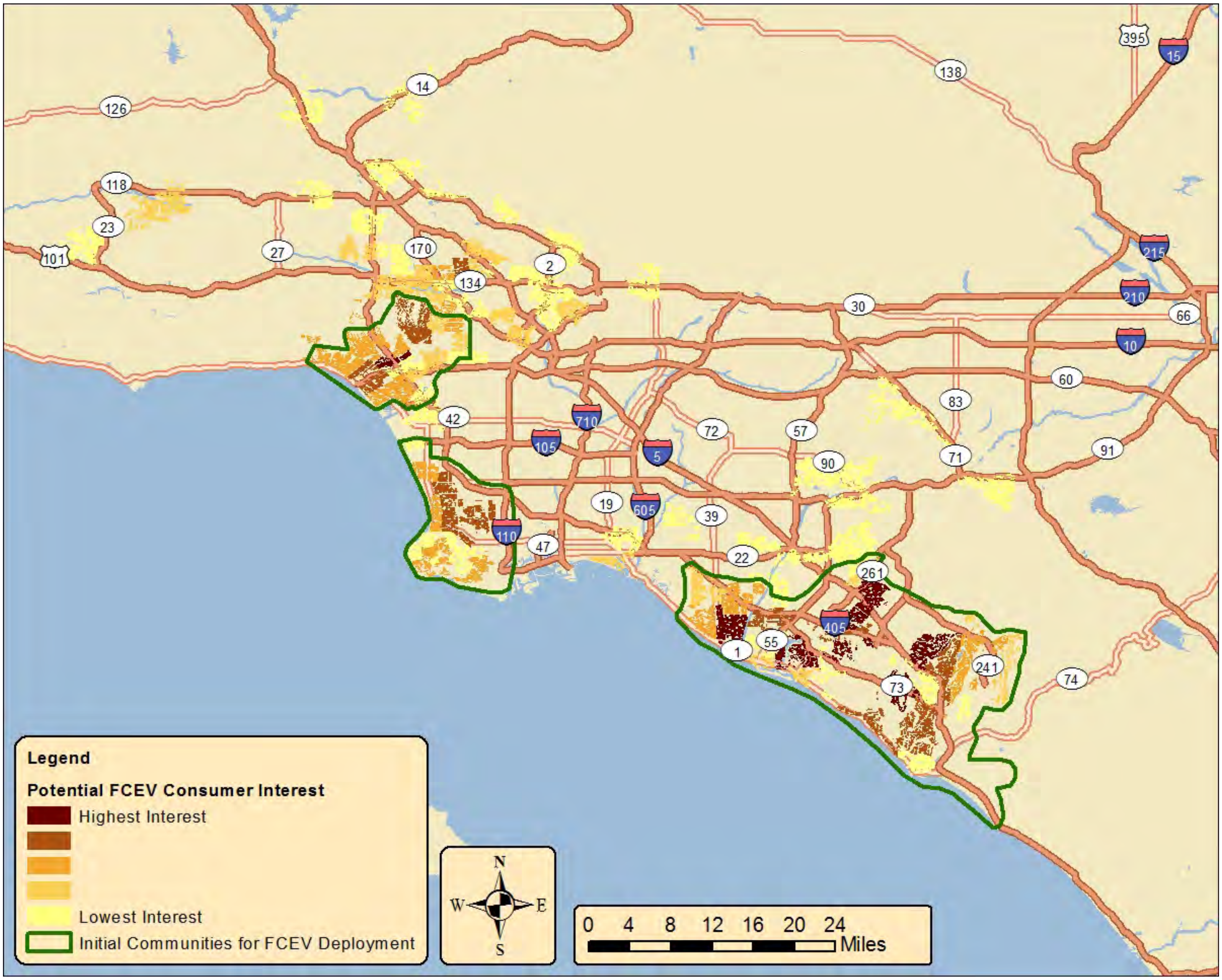


Source: UC Irvine

Analysis Confirmation

The selection and the corresponding selection method of these regions can be confirmed by comparison to the California Fuel Cell Partnership (CaFCP) automaker survey results and by proprietary market data collected by the National Fuel Cell Research Center at UC Irvine from several automakers. Figure 21 shows detailed market information specified by ZIP code as provided confidentially by several automakers. The confidential information has been merged so as not to reveal proprietary details. The data have been refined to show only residential areas, and the same three Southern California market regions have been again outlined in green. As shown, the areas of highest interest fall within the regions previously designated.

Figure 21: Agglomeration of Automaker Market Information Showing Potential Fuel Cell Electric Vehicle Consumer Interest Specified by Residential ZIP Code Area

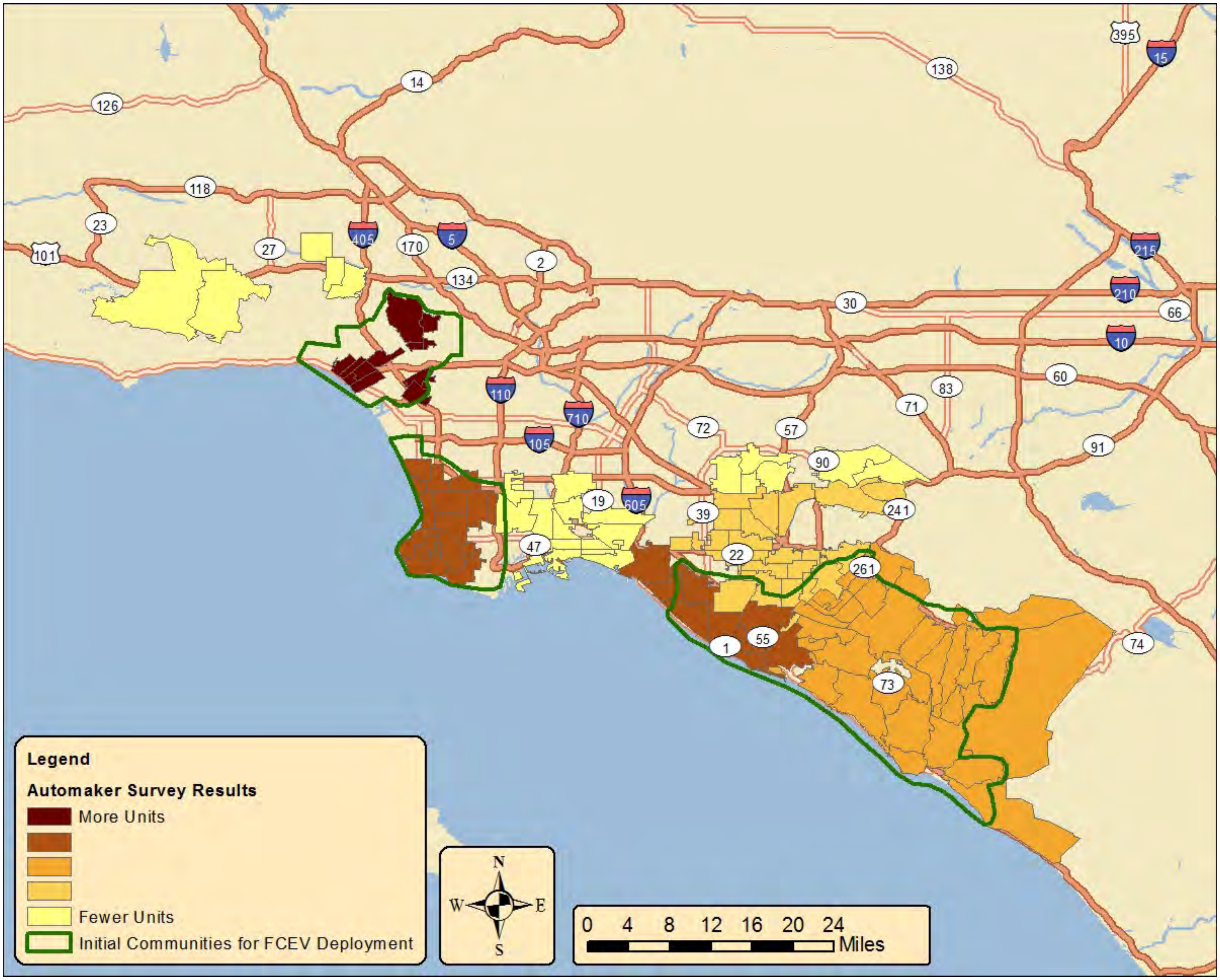


Source: UC Irvine

Figure 22 shows similar, though coarser, information provided by a CaFCP blind survey of automaker deployment plans [4]. These data include contributions from all automaker members of the CaFCP and indicate vehicle deployments, not by ZIP code, but by South Coast Air Quality Management District air monitoring zones. Again, the sectors of greatest deployment align well with the regions as drawn with green outlines.

The three sources of data align with respect to the three broad Southern California market areas. This alignment provides confidence in the analysis method, enabling designation of additional potential markets based on income, number of vehicles, and population.

Figure 22: CaFCP Automaker Survey Results Showing Potential Fuel Cell Electric Vehicle Deployment Areas in Southern California



Source: UC Irvine

Additional Markets Near Los Angeles

Using demographic data, additional early fuel cell electric vehicle markets can be identified for other areas of California. As shown in Figure 23, areas north of the designated Orange County region (Anaheim, Yorba Linda, and surrounding areas) and both east and west of the Santa

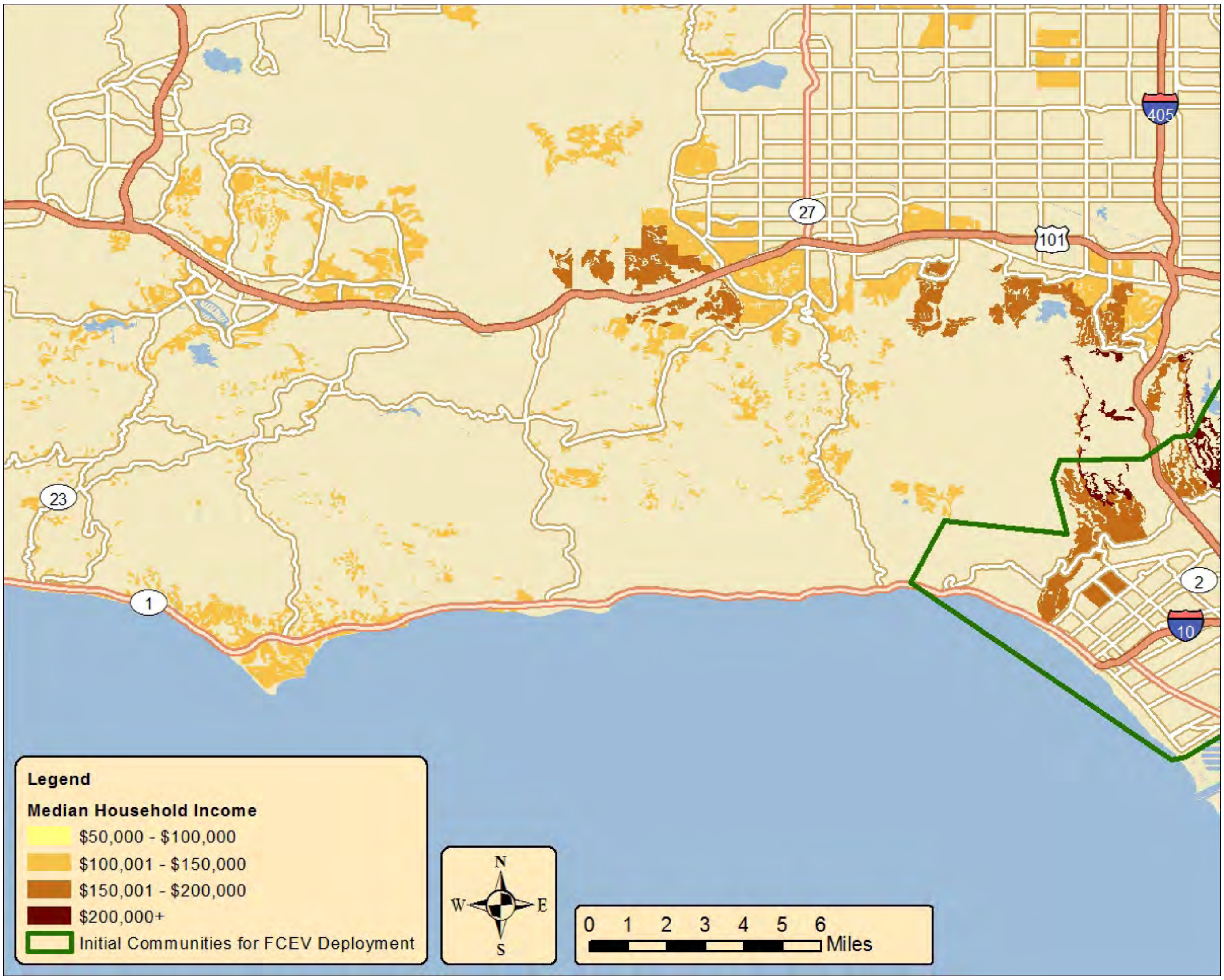
Monica region (San Fernando Valley and Pasadena areas, respectively) look particularly attractive for fuel cell electric vehicle markets, based on demographic data.

Figure 23: Attractive Fuel Cell Electric Vehicle Market Areas Based on Median Household Income, Population Density, and Vehicle Ownership

Source: UC Irvine

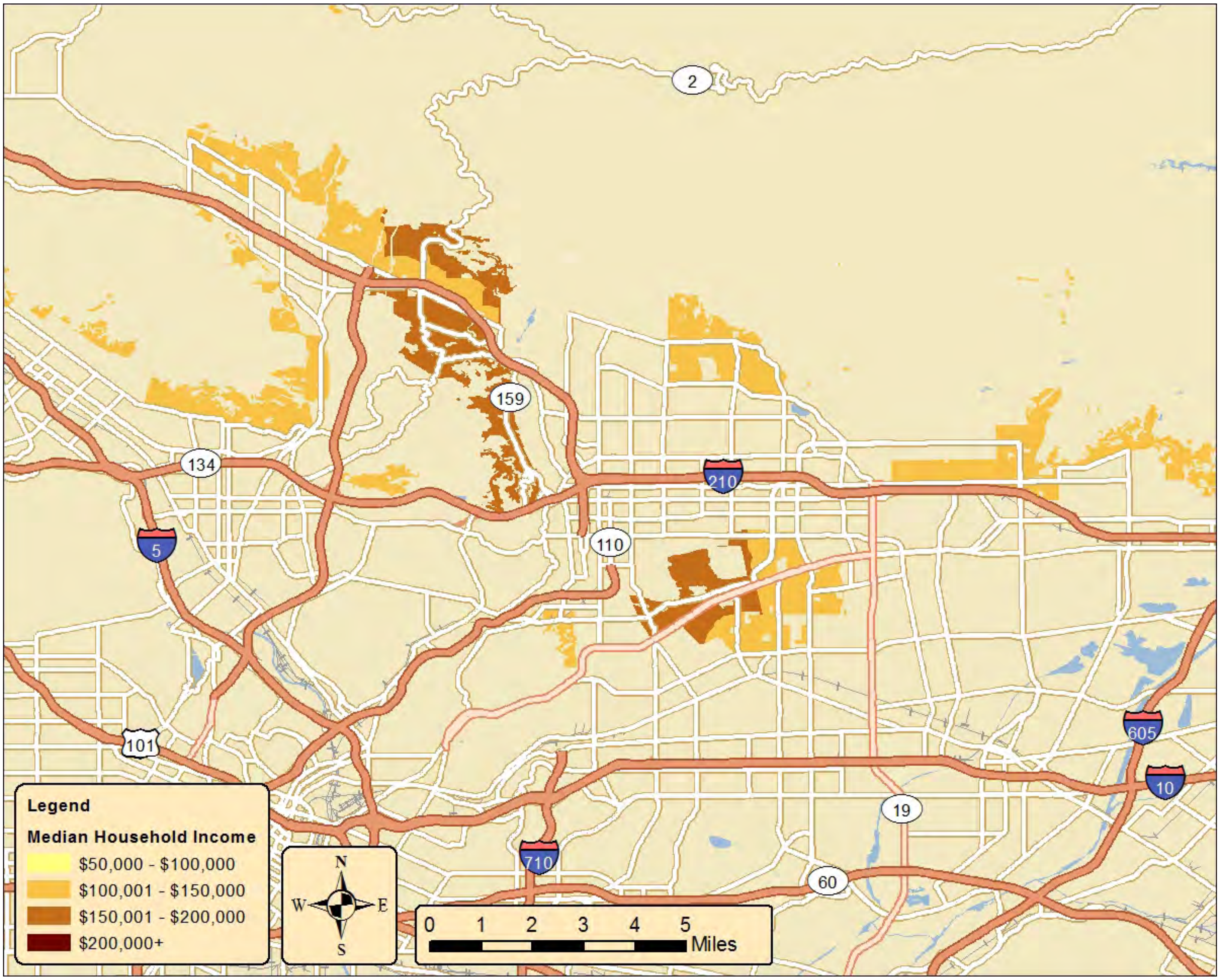
Figure 24 maps median household income near attractive potential fuel cell electric vehicle market areas in the San Fernando Valley area, west of the Santa Monica region. Figure 25 shows similar potential market areas around Pasadena.

Figure 24: Median Household Income by Census Tract [20] for Residential Areas in the San Fernando Valley Having Household Income Greater Than $100,000 per Year



Source: UC Irvine

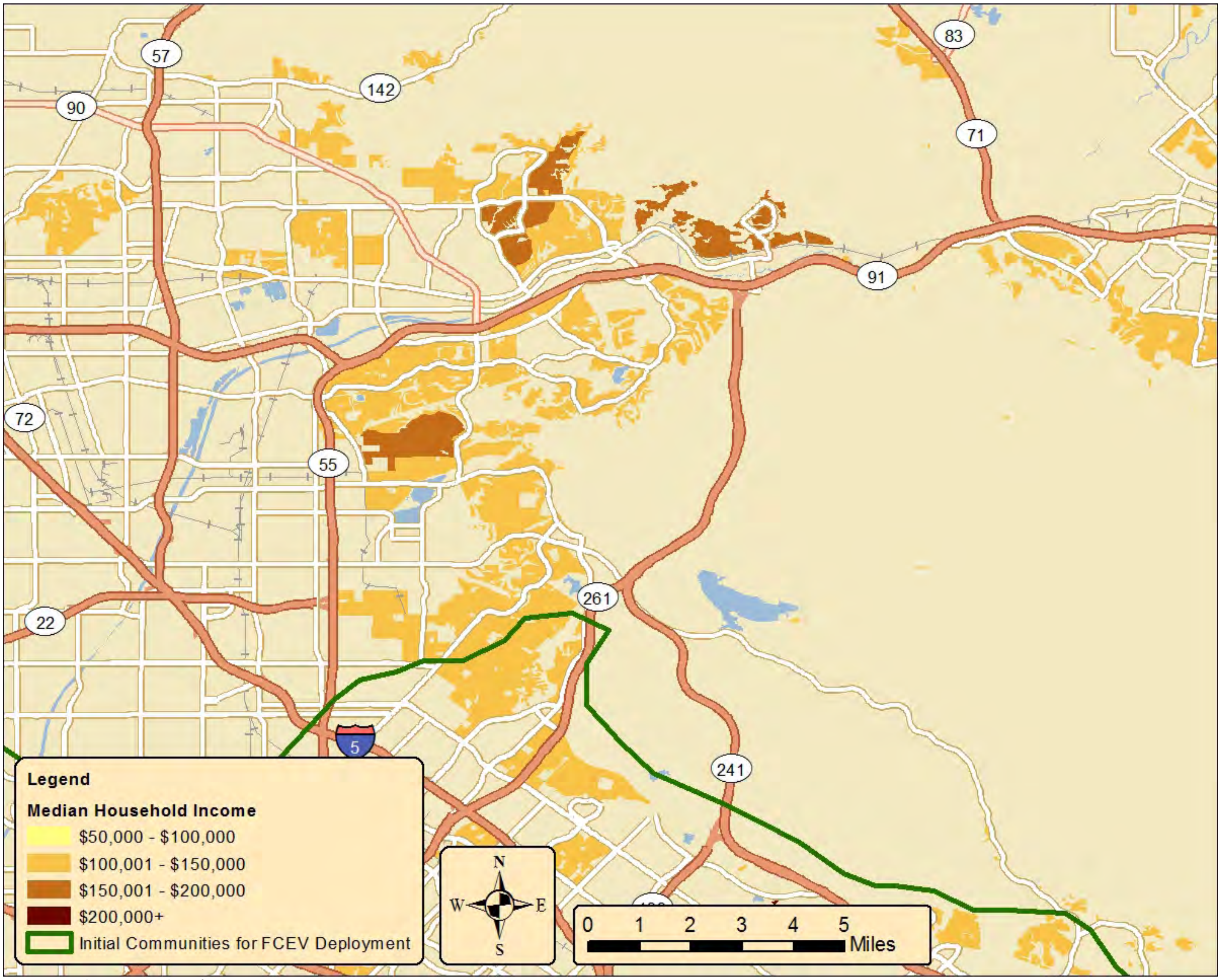
Figure 25: Median Household Income by Census Tract [20] for Residential Areas in the Pasadena Area Having Household Income Greater Than $100,000 per Year



Source: UC Irvine

Figure 26 indicates that the Anaheim and Yorba Linda areas north of the previously defined Orange County region are good potential fuel cell electric vehicle markets.

Figure 26: Median Household Income by Census Tract [20] for Residential Areas in the Anaheim Area Having Household Income Greater Than $100,000 per year

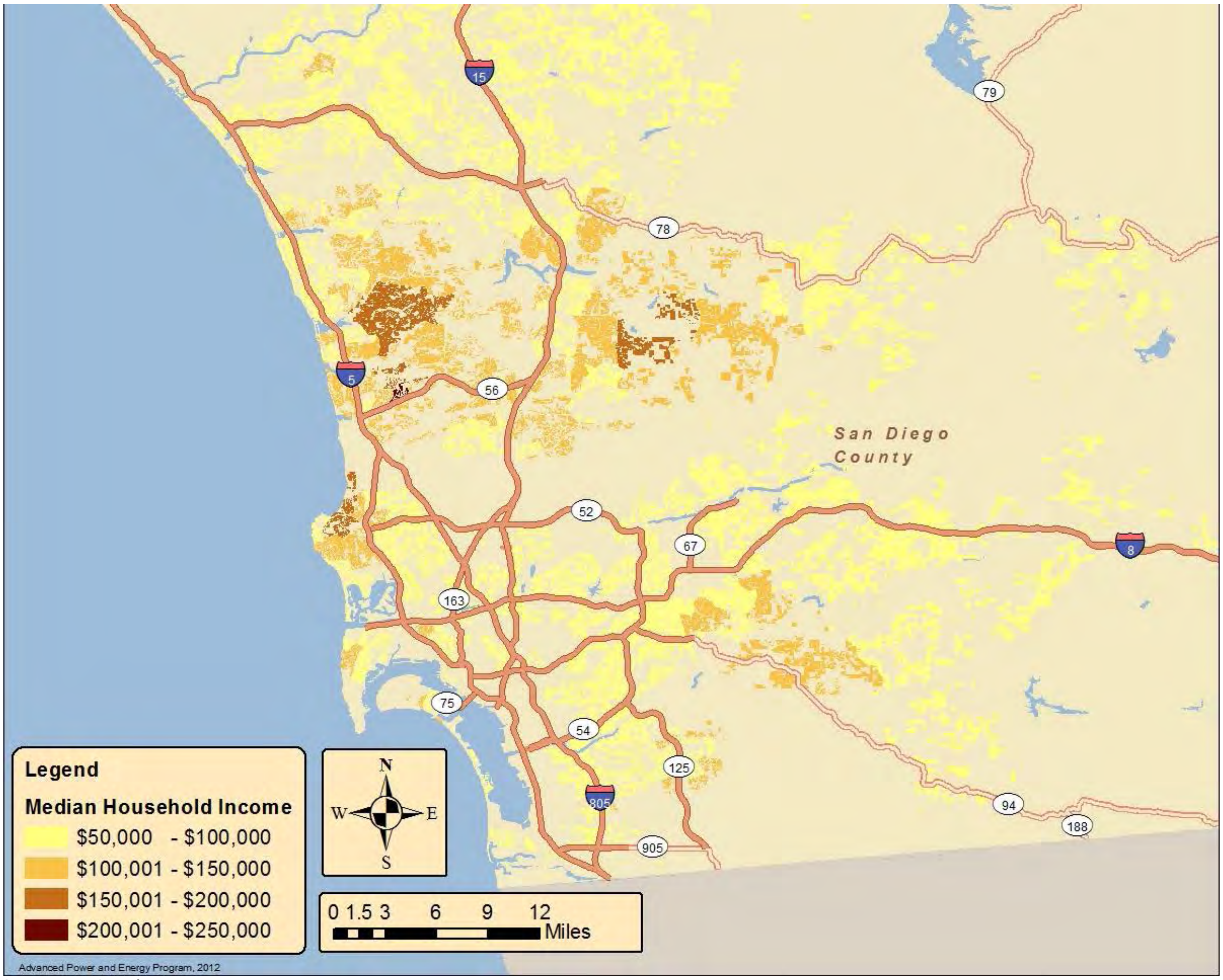


Source: UC Irvine

San Diego Area

Promising market regions exist on the north side of San Diego near Del Mar and La Jolla, as shown in Figure 27. Hydrogen stations located in these regions would have strong potential to serve as destination points for Los Angeles area residents, while serving as regional fuel cell electric vehicle deployment formation points for growing a San Diego market.

Figure 27: Gradient Showing Median Annual Household Income by Census Tract [20] for Residential Areas in the San Diego Area

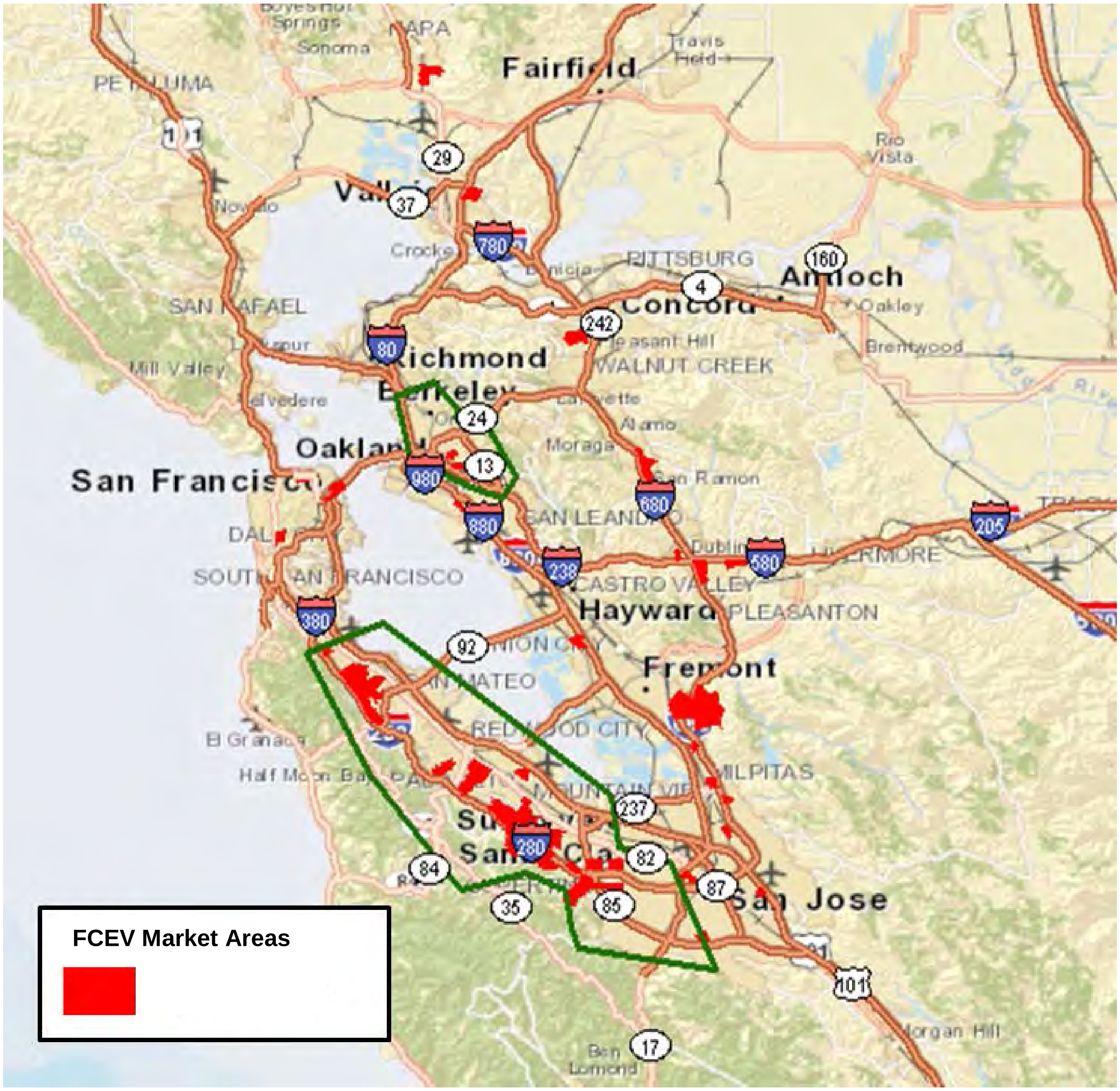


Source: UC Irvine

Northern California

The San Francisco Bay Area, as defined by the Association of Bay Area Governments (ABAG), consists of nine counties: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma. Promising fuel cell electric vehicle markets in this region can be characterized by regions north and south of the Golden Gate Bridge, a region located around the Berkeley area, and a region consisting of South Bay, as shown in Figure 28.

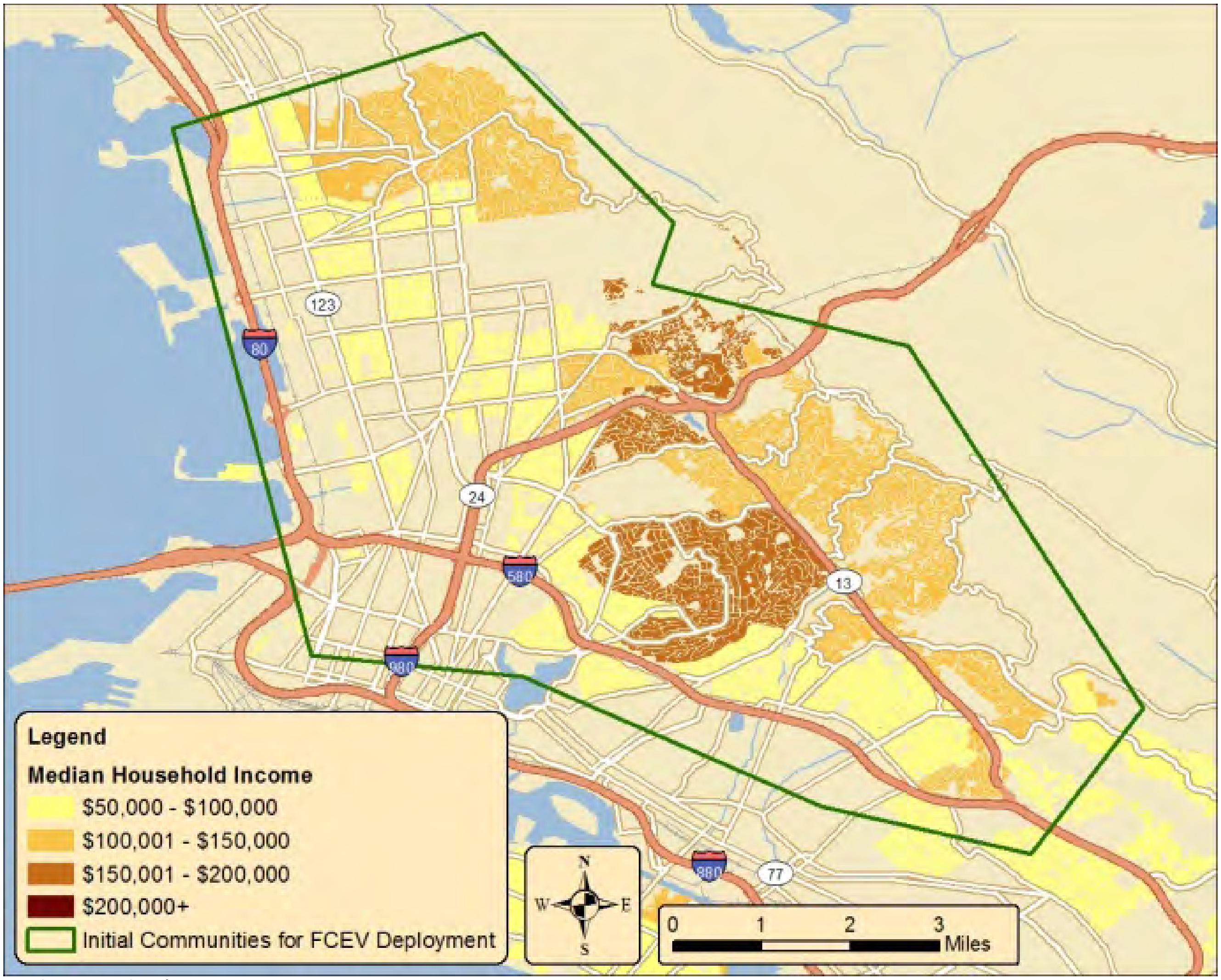
Figure 28: Attractive Fuel Cell Electric Vehicle Market Areas Based on Median Household Income, Population Density, and Vehicle Ownership in the San Francisco Bay Area



Source: UC Irvine

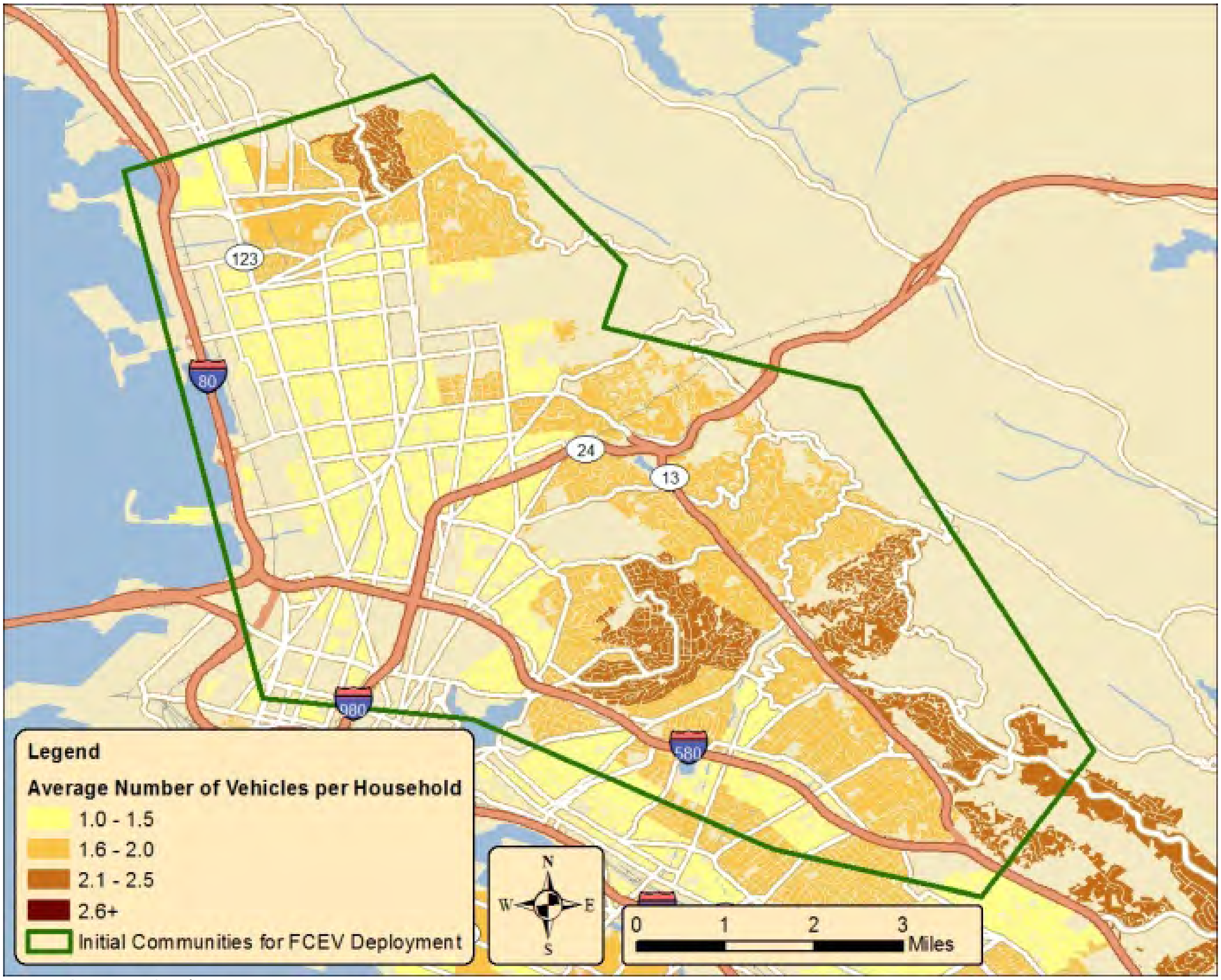
The Berkeley region has a total population of approximately 352,544 people living in about 150,481 households. Within this region, 36,512 households report annual incomes greater than $125,000. Figure 29 shows the median household income for this region. Figure 30 shows a similar map for number of vehicles per household. Figure 31 shows population. Again, many of the areas with high incomes also have more vehicles. 65,339 households possess two or more vehicles.

Figure 29: Gradient Showing Median Annual Household Income by Census Tract [20] for Residential Areas in the Berkeley Region



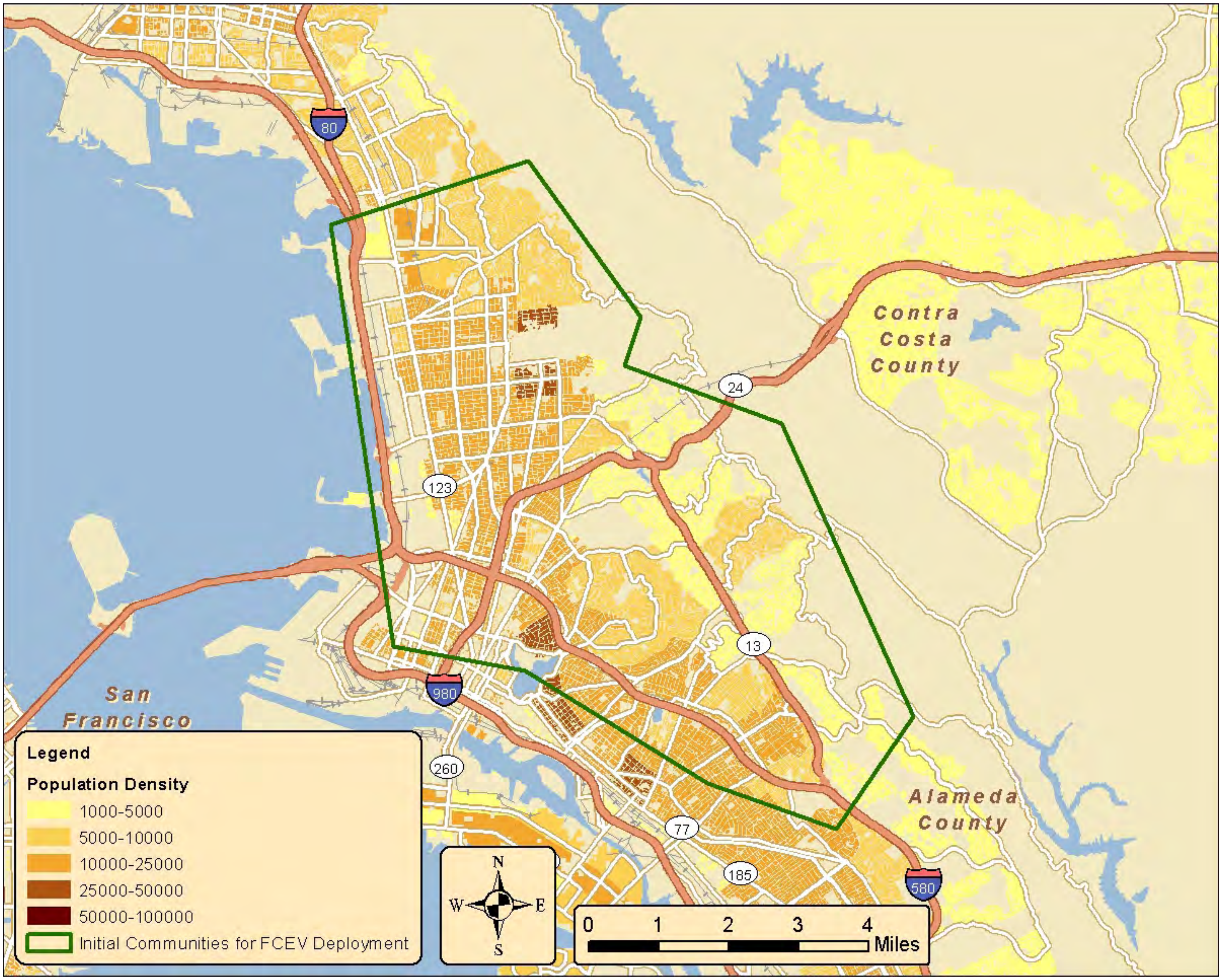
Source: UC Irvine

Figure 30: Gradient Showing Average Number of Vehicles per Household by Census Tract [20] for Residential Areas in the Berkeley Region



Source: UC Irvine

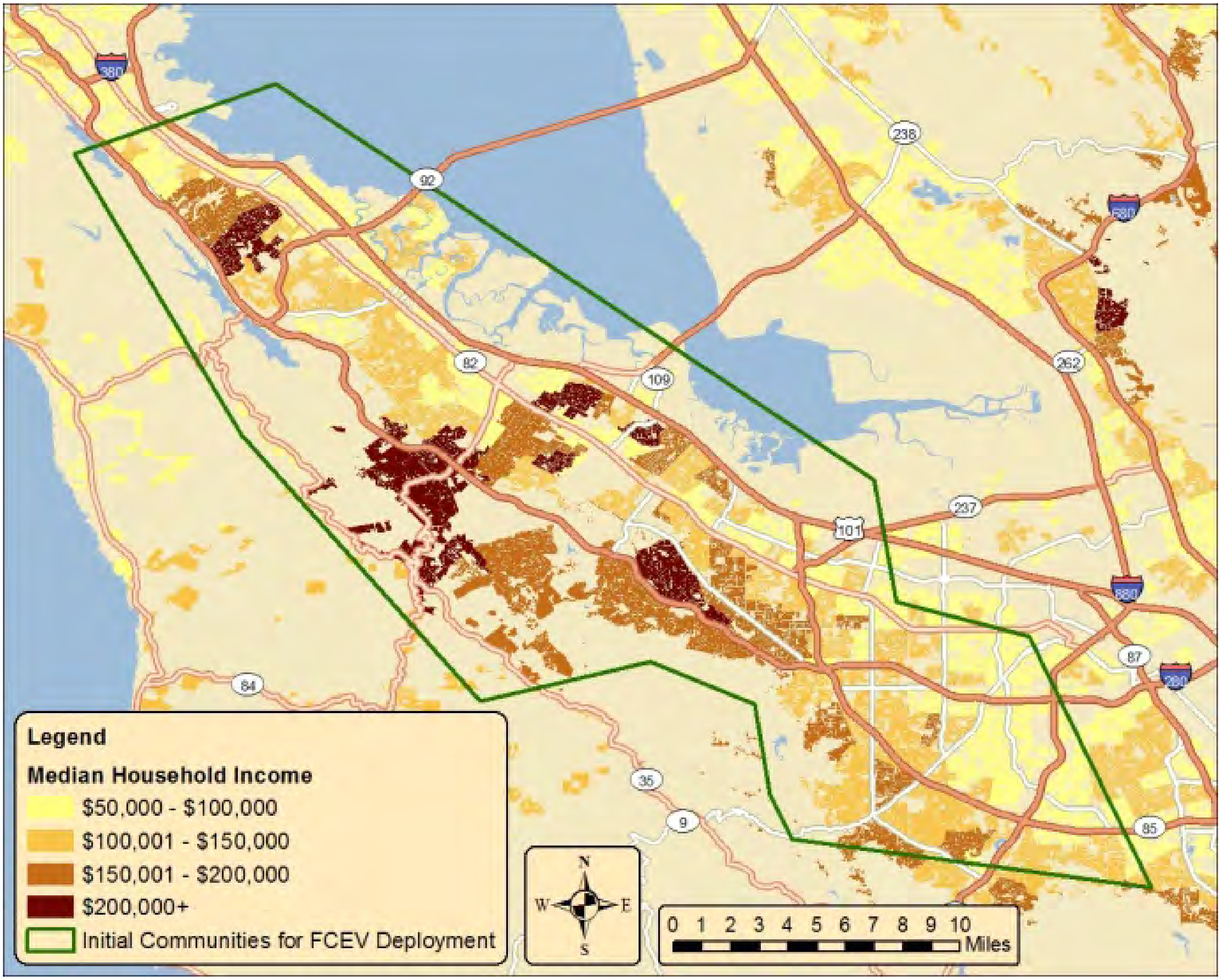
Figure 31: Gradient Showing Population Density by Census Tract [20] for Residential Areas in the Berkeley Region



Source: UC Irvine

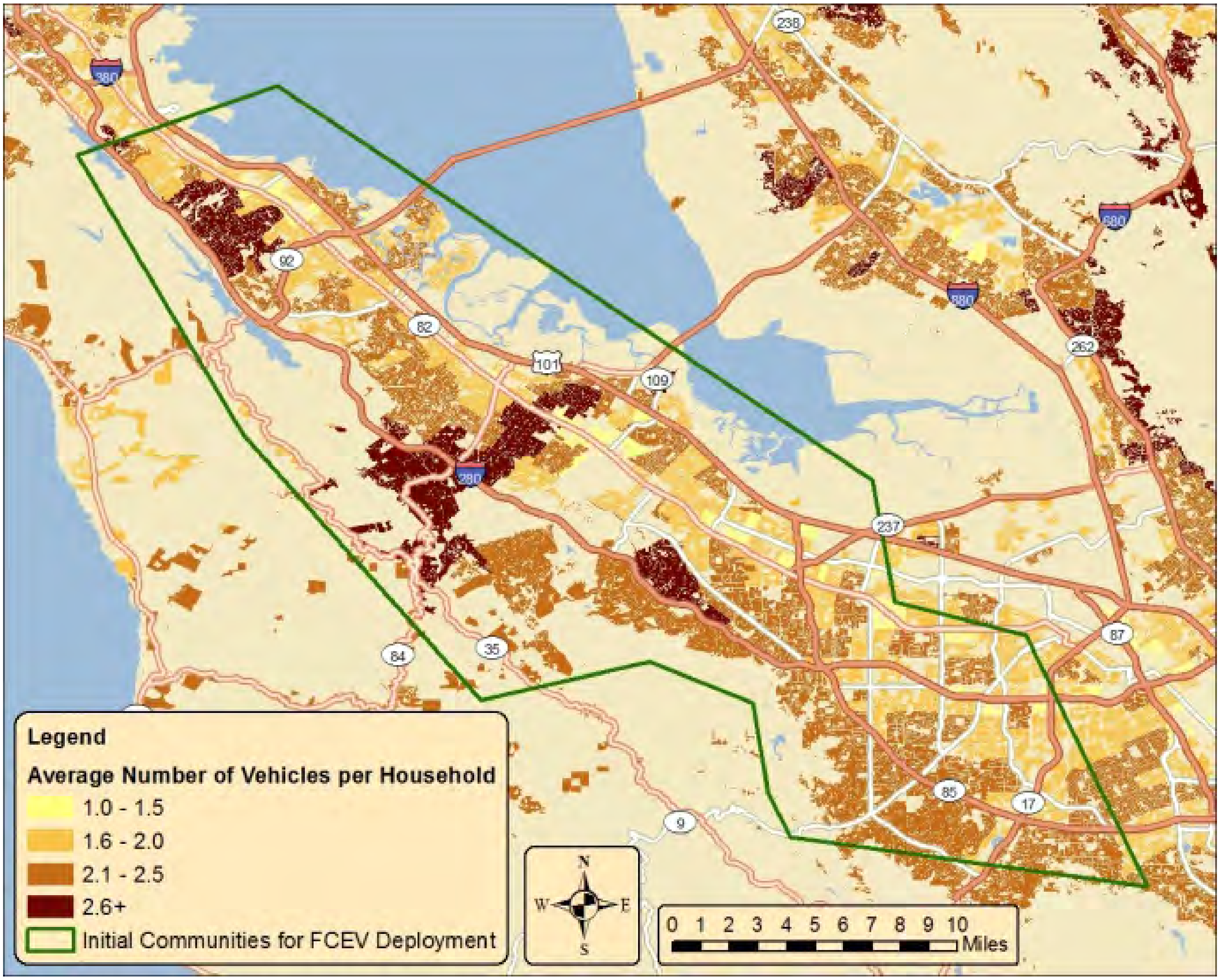
The San Francisco South Bay region has a total population of approximately 694,142 people living in about 263,449 households. Within this region, 99,561 households report annual incomes greater than $125,000. Figure 32 shows the median household income for this region. Figure 33 shows a similar map for number of vehicles per household. Figure 34 shows population. Again, many of the areas with high incomes also have more vehicles. 168,321 households possess two or more vehicles.

Figure 32: Gradient Showing Median Annual Household Income by Census Tract [20] for Residential Areas in the South Bay Region



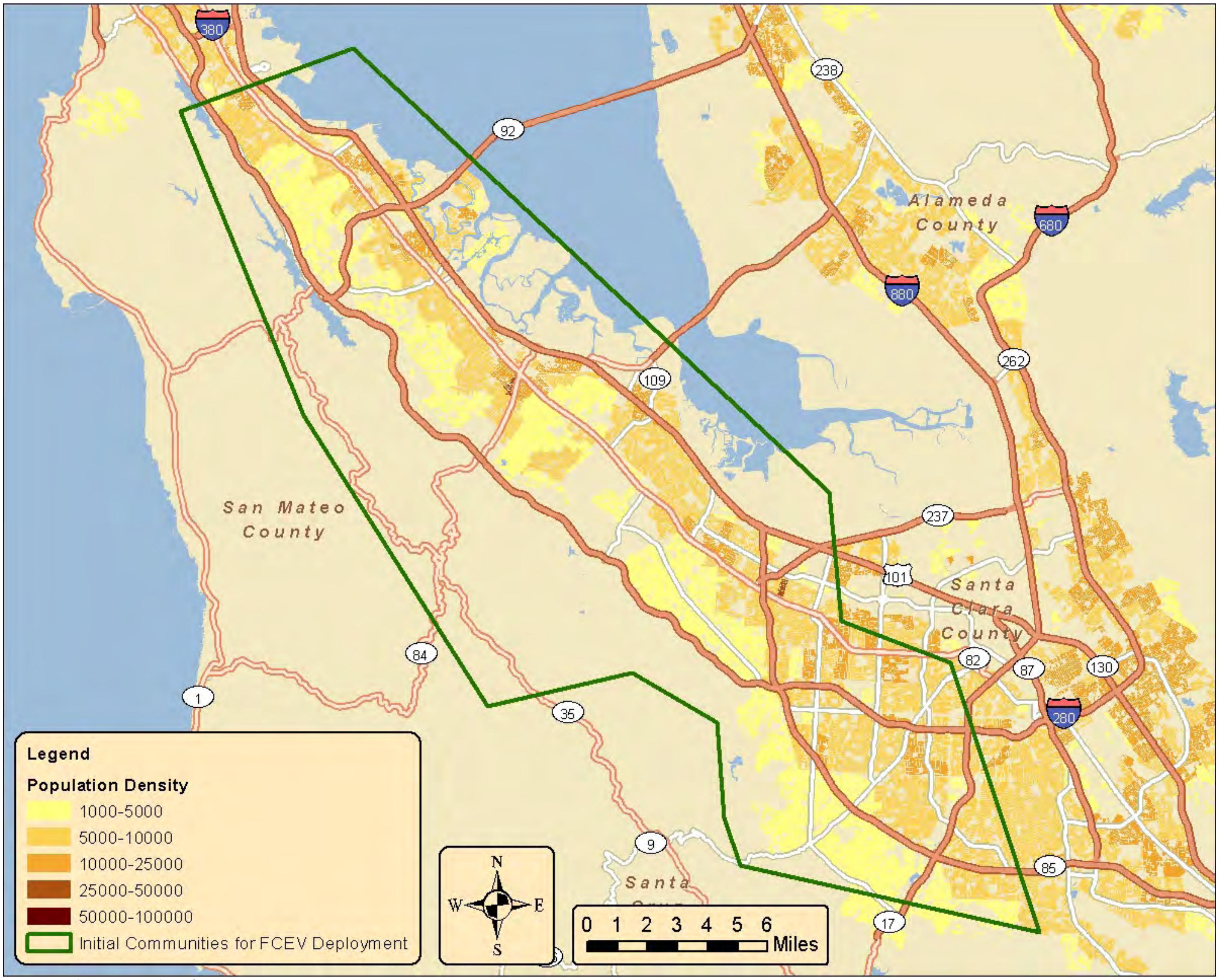
Source: UC Irvine

Figure 33: Gradient Showing Average Number of Vehicles per Household by Census Tract [20] for Residential Areas in the South Bay Region



Source: UC Irvine

Figure 34: Gradient Showing Population Density by Census Tract [20] for Residential Areas in the South Bay Region



Source: UC Irvine

CHAPTER 2: Planned and Existing Hydrogen Infrastructure

Eighteen publicly accessible hydrogen stations are planned or operating in the Los Angeles and San Francisco Bay Areas, as shown in Figure 35 and Figure 36. (A station in Sacramento is not shown in these maps.) Through significant efforts of funding agencies, station developers, oil and industrial gas companies, and automakers, station locations are beginning to populate the regions of highest market potential.

Figure 35: Planned and Existing Publicly Accessible Hydrogen Stations Operating in the Los Angeles Area

Source: UC Irvine

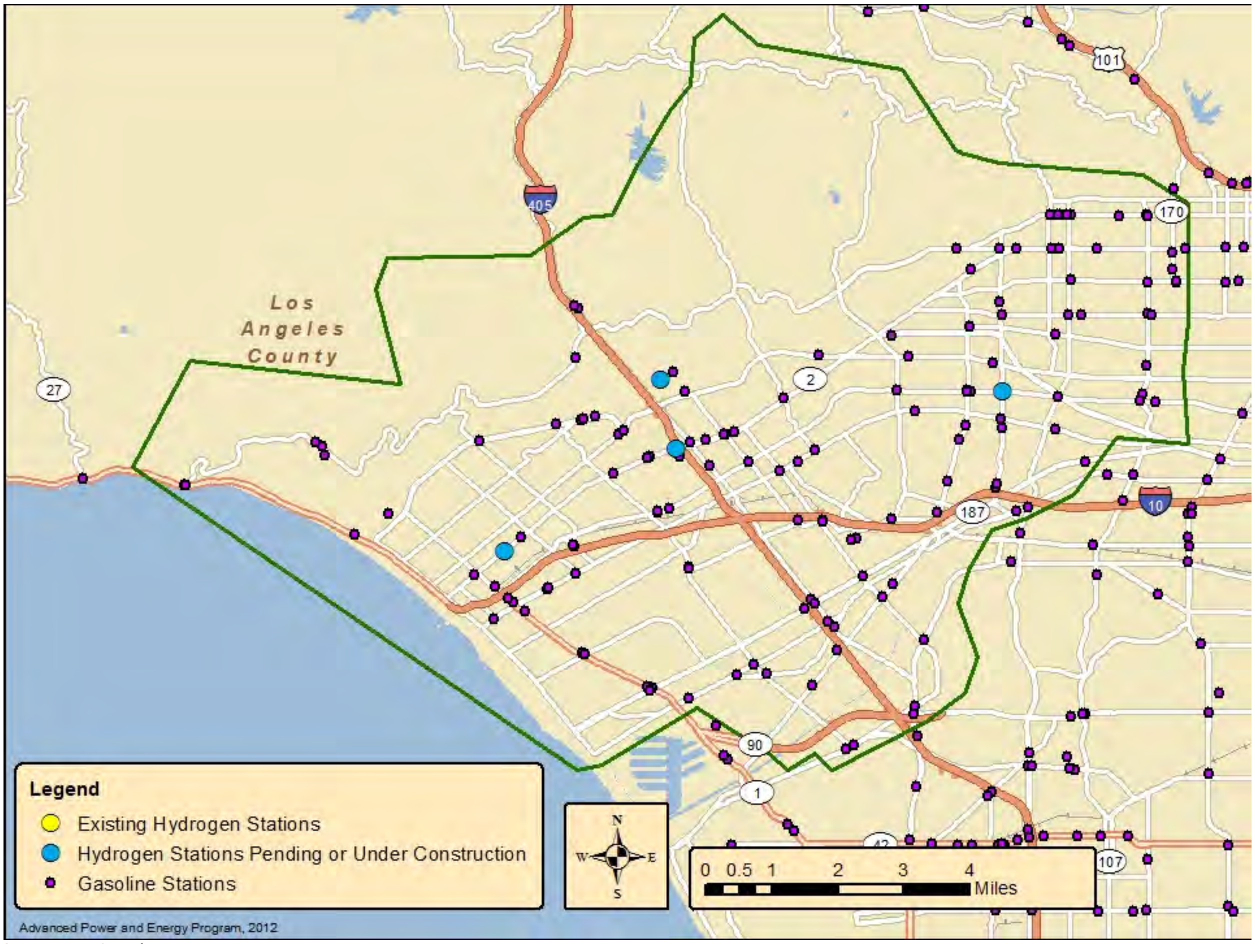
Figure 36: Planned and Existing Publicly Accessible Hydrogen Stations Operating in the San Francisco Bay Area

Source: UC Irvine

Analysis of Current Santa Monica Region Infrastructure

Figure 37 shows the existing gasoline station locations and the planned and existing hydrogen station locations for the Santa Monica region. As drawn, this region contains 126 gasoline stations and 4 hydrogen stations.

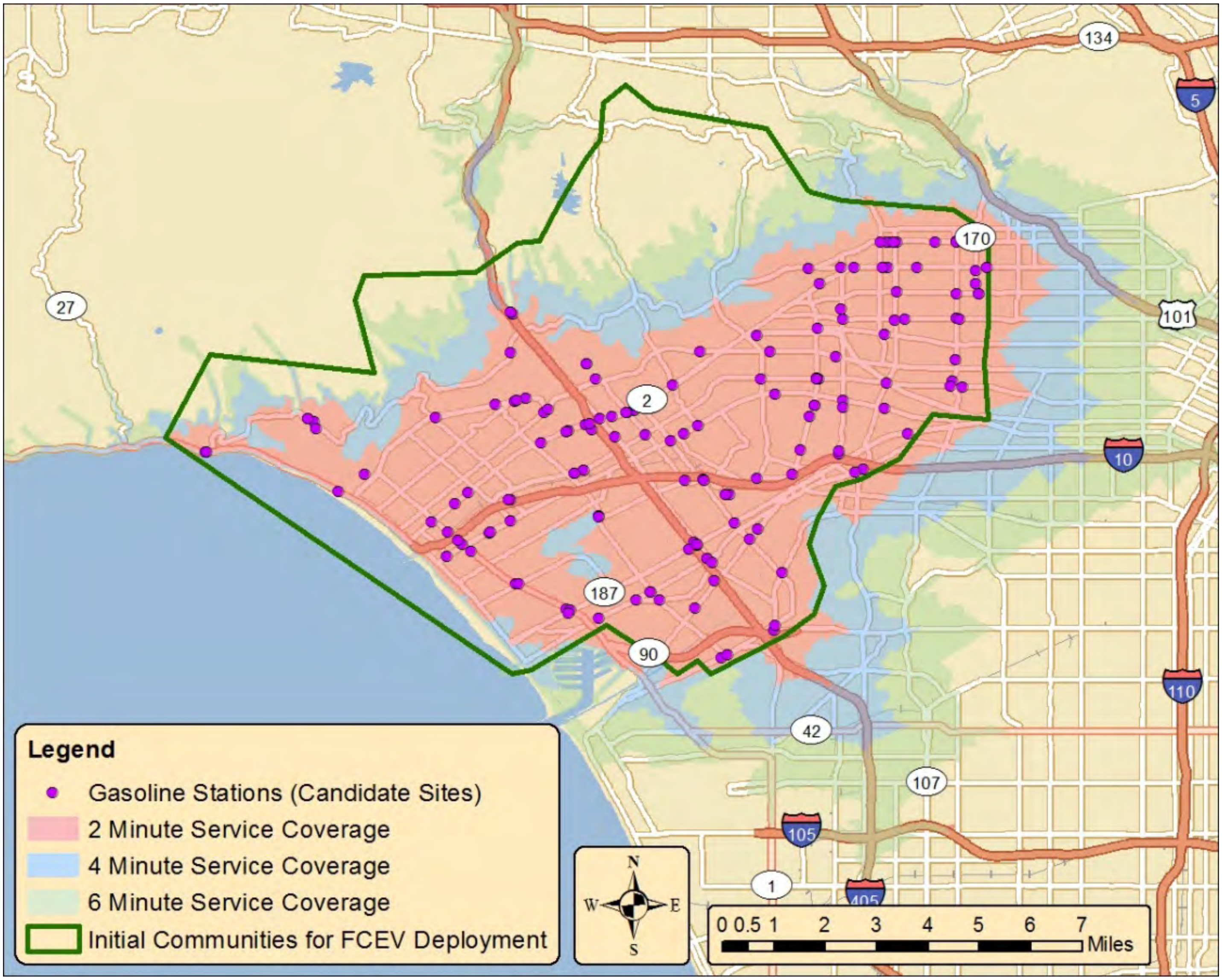
Figure 37: Existing Gasoline Stations and Planned and Existing Hydrogen Stations in the Santa Monica Region



Source: UC Irvine

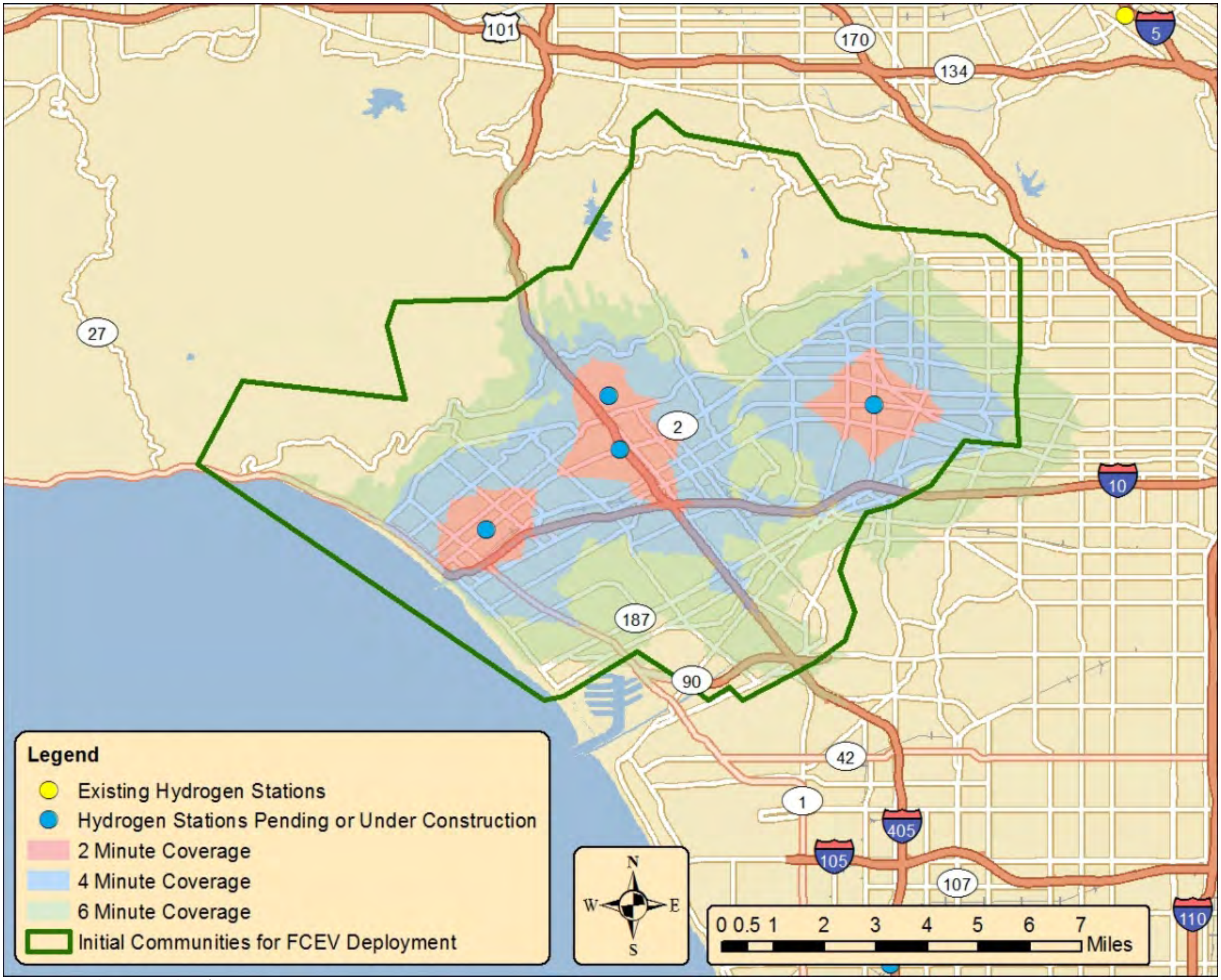
Geographic information systems (GIS) software can be used to determine maximum travel times from any location within the designated area to a fueling station. Such an analysis shows that the maximum travel time to a gasoline station is almost 4 minutes, but it takes a maximum of 10 minutes to reach one of the four hydrogen stations in the Santa Monica region. These results can be confirmed visually by the travel time contour plots shown in Figure 38 and Figure 39. As shown, gasoline stations provide very good coverage in the 2-, 4-, and 6-minute ranges. By contrast, the four hydrogen stations do not provide coverage that is nearly as comprehensive. A significant portion (more than 28 percent) of the designated area cannot reach a station in less than 6 minutes.

Figure 38: Travel Times Required to Reach Gasoline Stations in the Santa Monica Region



Source: UC Irvine

Figure 39: Travel Times Required to Hydrogen Stations in the Santa Monica Region



Source: UC Irvine

Table 3 and Table 4 quantitatively compare the coverage provided by 126 gasoline stations to that of the 4 hydrogen stations.

Table 3: Portion of Residential Land Covered by Gasoline and Hydrogen Infrastructure

Travel Time (min)	126 Gasoline Stations	4 Hydrogen Stations
6	93.6%	71.8%
4	87.0%	40.2%
2	74.4%	8.3%

Source: UC Irvine

Table 4: Portion of Roadway Covered by Gasoline and Hydrogen Infrastructure

Travel Time (min)	126 Gasoline Stations	4 Hydrogen Stations
6	94.6%	74.8%
4	90.2%	44.4%
2	78.7%	11.00%

Source: UC Irvine

These results indicate that more stations are required for hydrogen infrastructure to match the coverage of existing gasoline stations in the Santa Monica region. Similar analyses of the other initial market regions in California present similar or lower levels of hydrogen station coverage.

CHAPTER 3:
Station Location Optimization Method

Determining the Optimum Number of Hydrogen Fueling Stations Using Travel Time Analysis and Land Use (Santa Monica Case Study)

The research team combined publicly available data from the California Energy Commission [1] with other data from an investigation of public resources to determine that 126 gasoline stations, as shown in Figure 40, operate in the Santa Monica region. The team designed and used a relatively simple roadway network in the region to perform a travel time analysis. The analysis employs System 1 in a set covering model [16]. The shortest path is calculated between intersections and gasoline stations in the region to determine the greatest travel time to an existing gasoline station from anywhere within the region. Constraint (1-2) in combination with Objective Function (1-1) produce the general set covering analysis used to determine the number and location of hydrogen fueling stations that guarantee the same minimum travel time as existing gasoline stations.

System 1

$$Minimize \sum_{j} X_j \tag{1-1}$$

Such that:

$$\sum_{\forall j} Y_{ij} \cdot X \geq 1 \quad \forall i \tag{1-2}$$

$$Z_j \cdot X_j = 0 \quad \forall j \; at\ sites\ with\ no\ existing\ H_2\ fueling\ station \tag{1-3}$$

$$X_j = 1 \quad \forall j \; at\; sites\; with\; an\; existing\; H_2\; fueling\; station \tag{1-4}$$

$$X_j \in \{0,1\} \quad \forall j$$

$$Y_j \in \{0,1\} \quad \forall j$$

$$Z_j \in \{0,1\} \quad \forall j$$

Where:

$$Y_{ij} = \begin{cases} 1 & if\; candidate\; site\; j\; is\; within\; an\; acceptable\; travel\; time\; of\; intersection\; i \\ 0 & if\; candidate\; site\; j\; is\; not\; within\; an\; acceptable\; travel\; time\; of\; intersection\; i \end{cases}$$

$$Z_j = \begin{cases} 1 & if\; intersection\; j\; is\; not\; a\; candidate\; site \\ 0 & if\; intersection\; j\; is\; a\; candidate\; site \end{cases}$$

$$X_j = \begin{cases} 1 & if\; solution\; is\; located\; at\; a\; candidate\; site \\ 0 & if\; solution\; is\; not\; located\; at\; a\; candidate\; site \end{cases}$$

The roadway network used for the travel time analysis, shown in Figure 40, is designed using the following assumptions:

- Trunk roads, primary distributors, and district distributors (for example, highways and major arterial roads) are designed into the roadway network; residential feeder roads and cul-de-sacs are initially neglected.
- A full range of vehicle speeds (according to speed limits) is assumed in the roadway network.
- One-way roads are treated as two-way roads.
- Freeway ramps, loop roads, and U-turns are neglected in the roadway network.

Figure 40: Coarse Roadway Network of Road Segments and Intersections Used to Determine Optimum Hydrogen Station Locations in the Santa Monica Region

Source: UC Irvine

Application of the travel time analysis to this coarsely designed network of roads shows that from within the region, a driver is guaranteed access to an existing gasoline station within 3.72 minutes. When every intersection is considered as a candidate site for a hydrogen fueling station, the same guaranteed driving time of 3.72 minutes is achievable with just 19 strategically located hydrogen fueling stations (4 planned stations, plus 15 additional). Because four hydrogen stations are operating or planned in the region, Constraint (1-4) is employed to indicate that the site has existing hydrogen fueling stations.

Not surprisingly, there are several solution sets whereby 19 hydrogen fueling stations can guarantee a minimum driving time equivalent to the existing gasoline station infrastructure. However, land-use constraints are applied to the travel time analysis, which reduces the number of possible solutions.

Land-use characteristics can be applied as a constraint to candidate sites for hydrogen fueling stations using (1-3). In this study, Constraint (1-3) is used to restrict candidate sites for hydrogen stations to existing gasoline station sites. The travel time analysis determines that even when imposing this restriction, a guaranteed minimum driving time of 3.72 minutes is still achievable with 19 hydrogen fueling stations. Even when imposing the restriction, several solution sets of 19 stations arranged in different configurations are produced by the travel time analysis. This result is fortuitous because existing gasoline stations are favorable sites for hydrogen stations.

From a land-use perspective, gasoline stations are already zoned and permitted for the retail sale of vehicular fuel. Also, the layout of these stations enables delivery of hydrogen via liquid or compressed gas tanker. Existing gasoline stations are generally well-positioned economically, which can help offset potentially low hydrogen sales in the early years, and there is typically an established infrastructure in the form of convenience store and restrooms.

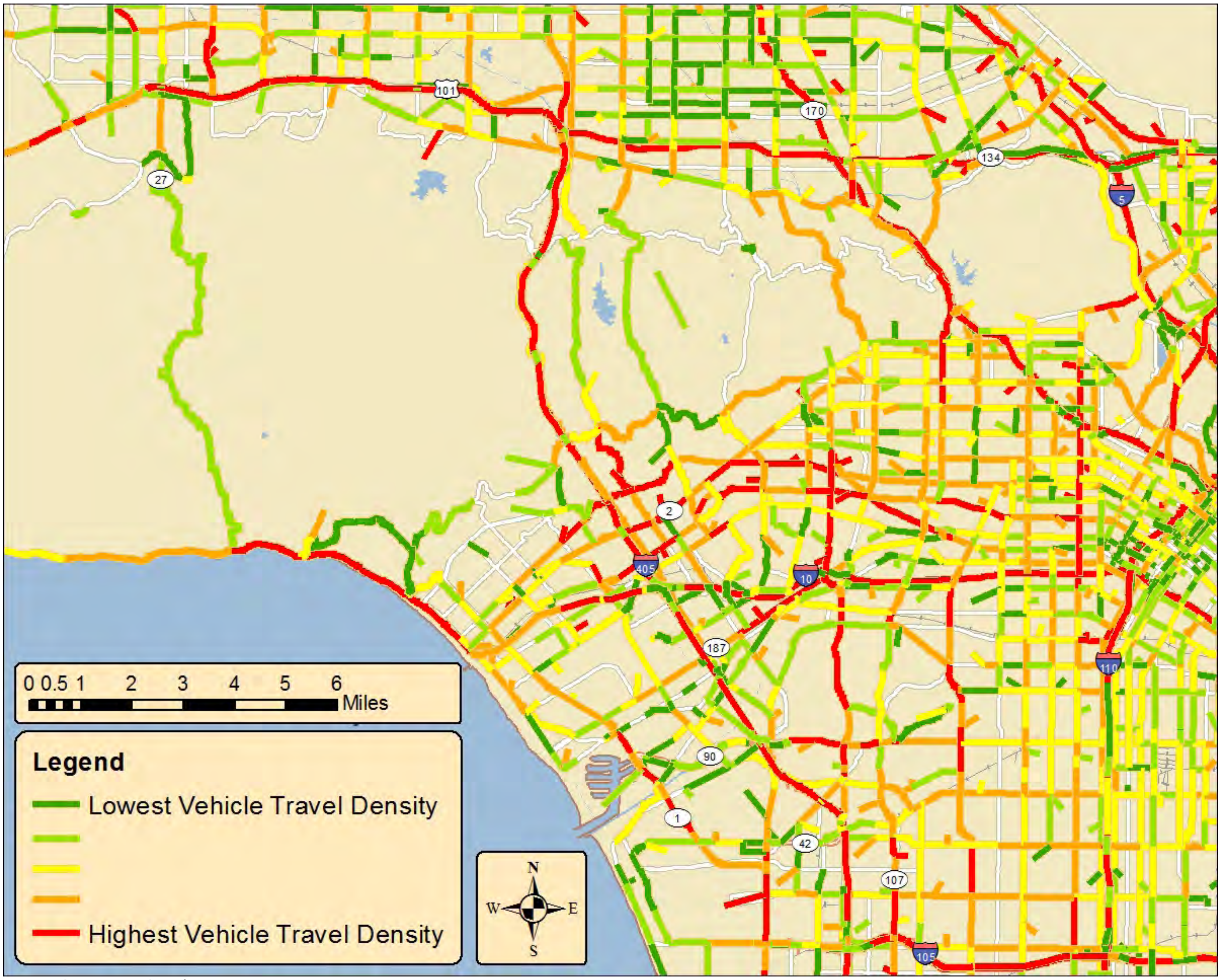
Results from the travel time problem with and without applying land-use constraints are used to generate strategic candidate sites for hydrogen fueling stations and determine that a minimum of 16 stations are required to provide a basic desired level of customer service (that is, guarantee a minimum travel time to hydrogen fueling stations comparable to that of existing gasoline stations for a driver within the region).

While land-use restrictions reduce the number of candidate sites for hydrogen fueling stations, the travel time analysis still results in several solution sets. Consideration of travel density enables solutions to be further differentiated.

Differentiating Optimum Locations for Hydrogen Fueling Stations Using Vehicle Travel Density

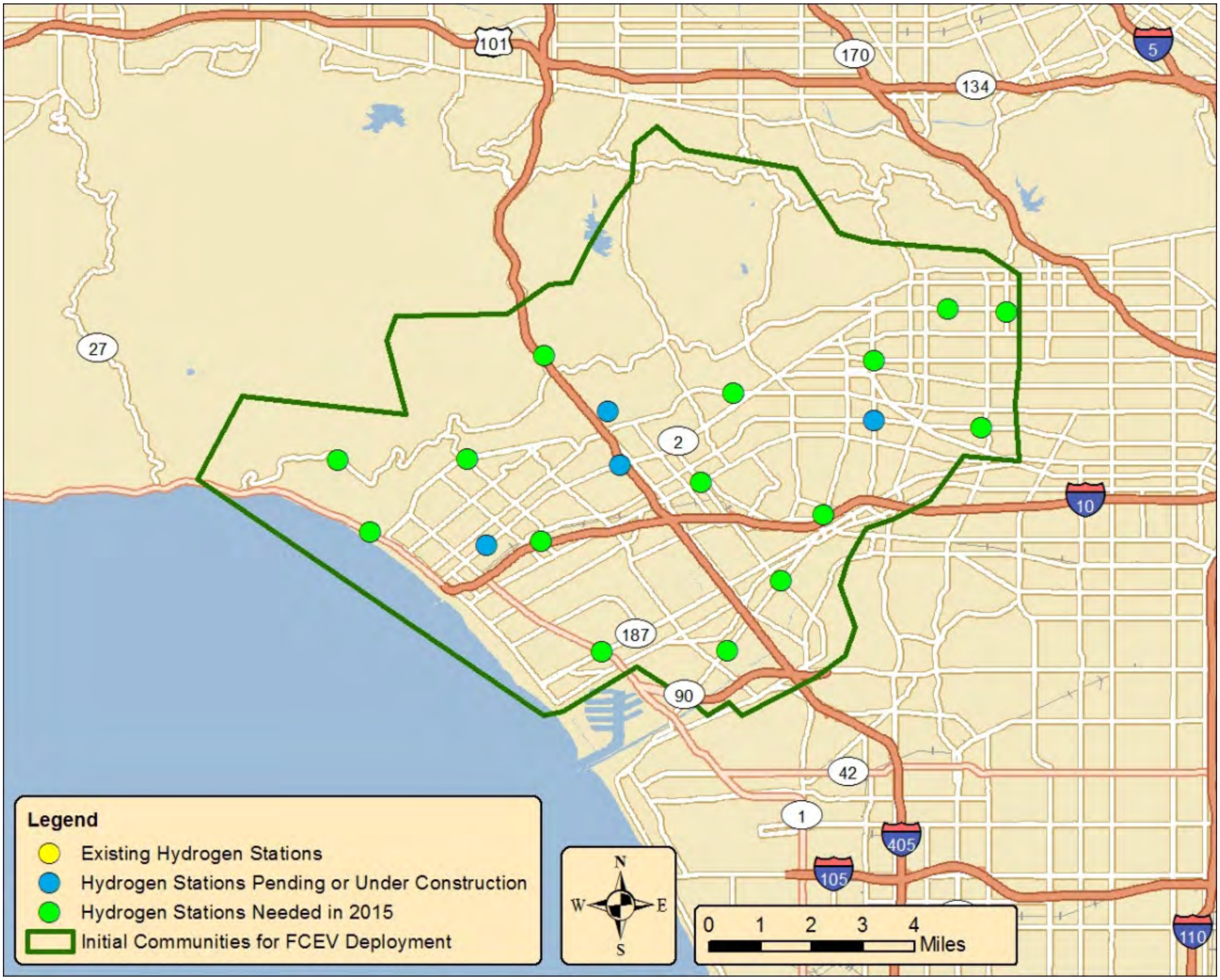
Placing hydrogen stations near locations with high travel density is an important aspect to station siting and enables solutions for the location of hydrogen fueling stations to be further differentiated [14]. The Orange County Transportation Analysis Model (OCTAM) provides a regional travel forecasting base for transportation planning. It incorporates state-of-the-practice modeling components that are consistent with the Southern California Regional Transportation Model released by the Southern California Association of Governments [2]. OCTAM is used to estimate daily passenger vehicle flows around Santa Monica. Morning on-road vehicle density is compared to afternoon on-road vehicle density to account for disparities that might occur between travel behavior in the morning and afternoon. Upon observation, differences in on-road vehicle density between the morning and afternoon are relatively minor. As a result, average weekday on-road vehicle density, shown in Figure 41, is used. Candidate sites for hydrogen fueling stations are given preference based on proximity to regions of high on-road vehicle density. This approach relates to previous studies that have shown that locating fueling stations near regions of high on-road vehicle density provides access to a larger fraction of customers with fueling needs [12]. Figure 42 shows the location of the 19 hydrogen stations required to match the travel coverage of the existing 126 gasoline stations.

Figure 41: Density of Vehicle Travel Flow in the Santa Monica Region



Source: UC Irvine

Figure 42: Existing, Planned, and Suggested Hydrogen Station Locations in the Santa Monica Region Required to Provide the Same Level of Coverage as the Existing Gasoline Station Network



Source: UC Irvine

Confirming the Optimized Number and Location of Hydrogen Fueling Stations Using Service Coverage

Service coverage provided by proposed hydrogen station configurations is analyzed to confirm that the number and location of hydrogen fueling stations in each of the configurations provide a basic level of service in the Santa Monica region similar to that of existing gasoline stations. This step is included in the method because, (1) due to the modeling complexity needed for the optimization routine, the roadway network used in the travel time analysis is unavoidably coarse, and (2) it provides the ability to compare service coverage over roads and residential land for several vehicular travel times. Station sites near residential areas are prioritized because

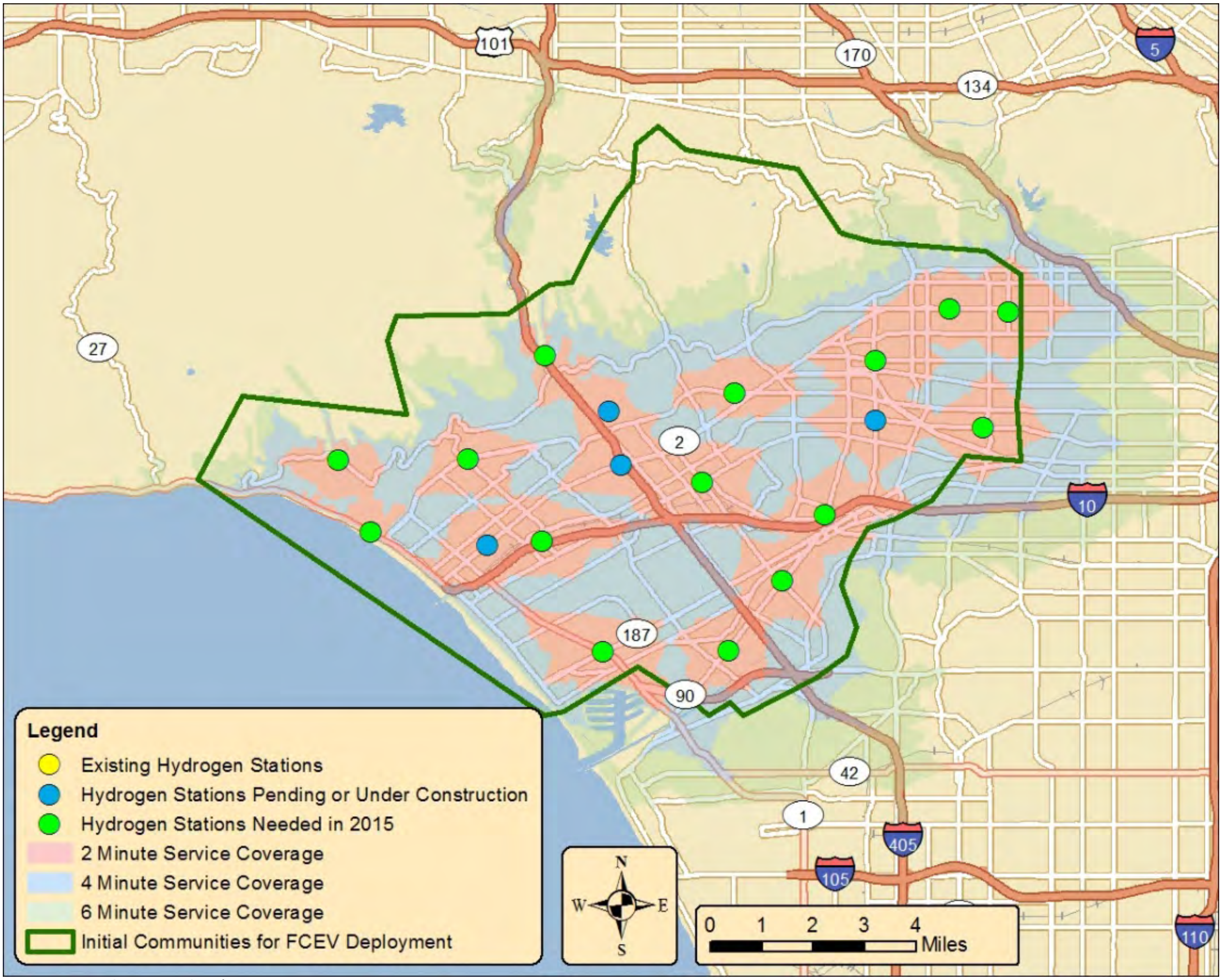
75 percent of refueling trips begin or end at home, drivers prefer to fuel near their homes, and 72 percent of refueling trips are within 5 minutes of a trip origin or destination [11].

To calculate service coverage, a highly resolved roadway network that incorporates geographic information systems (GIS) data are employed [3]. The GIS data roadway network includes:

- All roads.
- Comprehensive speed limit resolution (10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 65 miles per hour [MPH]).
- One-way roads.
- Freeway ramps.
- U-turns.

Service coverage provided by the hydrogen fueling station configurations is analyzed for 2, 4, and 6 minutes of driving time with respect to roads in the region and coverage of residential land. In other words, for each configuration of optimized candidate sites for hydrogen fueling stations, GIS data are used to determine the portion of roads and residential land accessible to those sites within 2, 4, and 6 minutes of driving time. Figure 43 shows the service coverage provided by the hydrogen fueling stations.

Figure 43: Service Coverage for Existing, Planned, and Proposed Hydrogen Stations in the Santa Monica Region



Source: UC Irvine

As a basis for comparison, the GIS-based roadway network is also used to analyze the service coverage provided by the 126 existing gasoline stations in the Santa Monica region. Service coverage is assessed with respect to roads by determining the portion of roads within reach of a proposed hydrogen fueling station in two, four, and six minutes of driving time.

Table 5 compares the portion of road miles in the Santa Monica region that are accessible by hydrogen stations, as well as by existing gasoline stations. Nineteen hydrogen fueling stations are nearly comparable to existing gasoline stations when considering a driving time of six or four minutes. However, within two minutes of driving time or less, existing gasoline stations provide service coverage to a significantly greater portion of roads compared to the hydrogen fueling stations.

Table 5: Portion of Roadway Covered by Gasoline and Hydrogen Infrastructure

Travel Time (min)	126 Gasoline Stations	19 Hydrogen Stations
6	94.6%	93.1%
4	90.2%	87.4%
2	78.7%	45.8%

Source: UC Irvine

Similarly, the research team assesses service coverage with respect to residential land by determining the portion of residential land that is accessible by the proposed configuration of hydrogen fueling stations within two, four, and six minutes of driving time. Table 6 shows the portion of residential land that can be reached by hydrogen stations in the proposed configuration, as well as by existing gasoline stations for comparison. Nineteen hydrogen stations can serve a nearly comparable portion of residential land as existing gasoline stations within six or four minutes. However, within two minutes or less, existing gasoline stations provide service to a significantly greater portion of residential land use compared to the proposed hydrogen stations.

Table 6: Portion of Residential Land Covered by Gasoline and Hydrogen Infrastructure

Travel Time (min)	126 Gasoline Stations	19 Hydrogen Stations
6	93.6%	91.7%
4	87.1%	84.1%
2	74.4%	43.1%

Source: UC Irvine

CHAPTER 4:
Hydrogen Stations Required to Match Gasoline Infrastructure

Los Angeles Regions

As outlined previously, three major regions of the greater Los Angeles area have been selected as initial market regions. Detailed station placement optimization within these regions can produce a level of service for fuel cell electric vehicle customers equivalent to that of existing gasoline stations, with significantly fewer station locations.

Santa Monica Region

The Santa Monica region has four planned hydrogen stations located at the addresses listed in Table 7.

Table 7: Location of Existing and Planned Hydrogen Stations in the Santa Monica Region

Location	Status	Capacity
1402 Santa Monica Boulevard, Santa Monica, CA 90404	Pending	180 kg/day
1004 S. La Cienega Boulevard, Los Angeles, CA 9035	Pending	180 kg/day
11261 Santa Monica Boulevard, Los Angeles, CA 90025	Pending	180 kg/day
University of California, Los Angeles	Pending	140 kg/day

Source: UC Irvine

An additional 15 stations, for a total of 19, are proposed by the analysis herein to complete a regional network with service coverage comparable to the existing 126 gasoline stations (15.1 percent). Figure 43 shows location and service coverage of the proposed Santa Monica region hydrogen station network.

Torrance Region

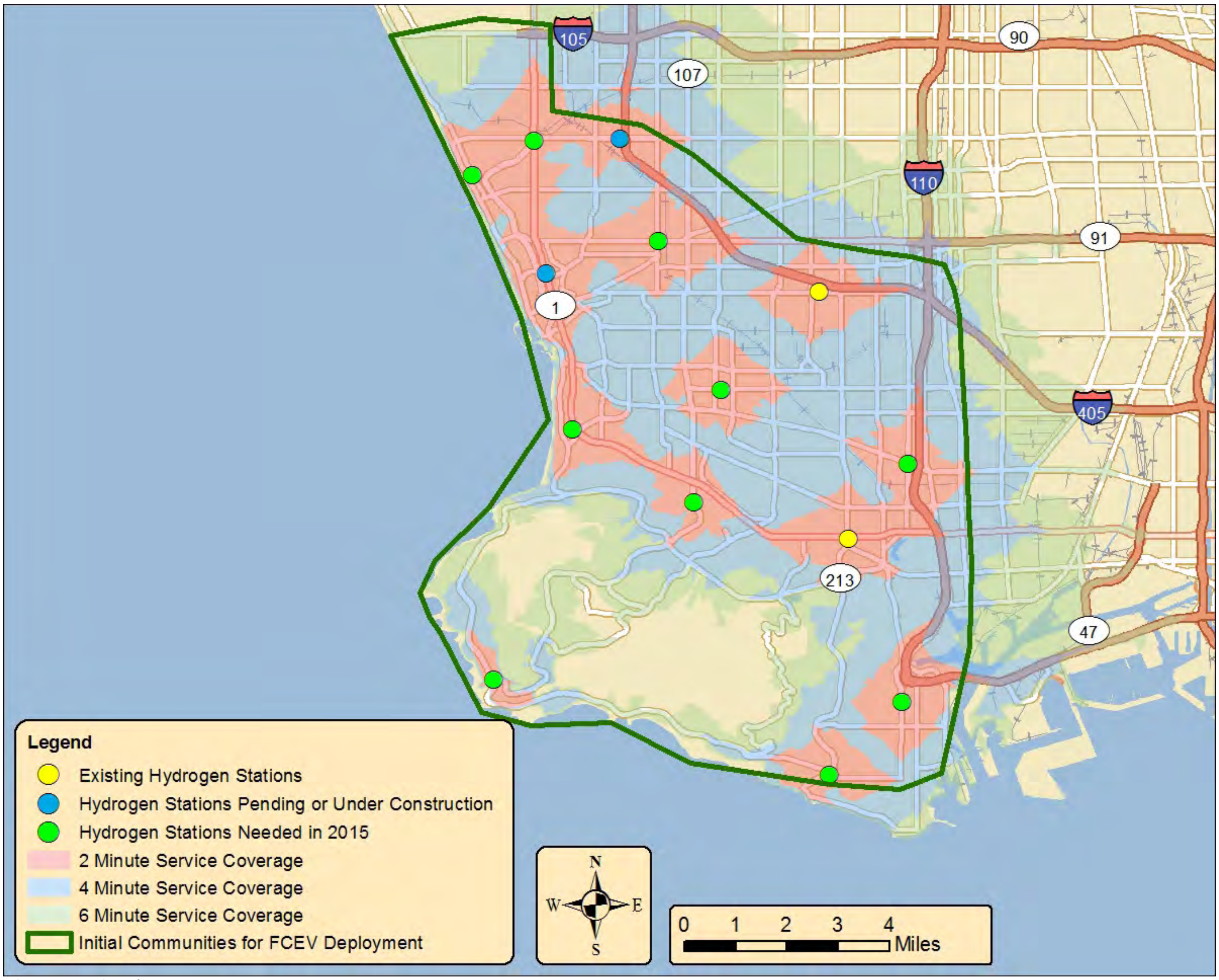
The Torrance region has one existing and three planned hydrogen stations located at the addresses listed in Table 8. An additional 10 stations, for a total of 14, are proposed by the analysis herein to complete a regional network with service coverage comparable to the existing 119 gasoline stations (11.7 percent). Figure 44 shows location and service coverage of the proposed Torrance region hydrogen station network.

Table 8: Location of Existing and Planned Hydrogen Stations in the Torrance Region

Location	Status	Capacity
1131 Pacific Coast Highway, Hermosa Beach, CA 90254	Pending	180 kg/day
5230 Rosecrans Avenue, Hawthorne, CA 90250	Pending	180 kg/day
25800 S. Western Ave Harbor City, CA 90710	Pending	100 kg/day
2051 W. 190th Street Torrance, CA 90501	Operational	50 kg/day

Source: UC Irvine

Figure 44: Existing, Planned, and Suggested Hydrogen Stations in the Torrance Region Required to Provide the Same Level of Service as the Existing Gasoline Station Infrastructure in the Region



Source: UC Irvine

Orange County Region

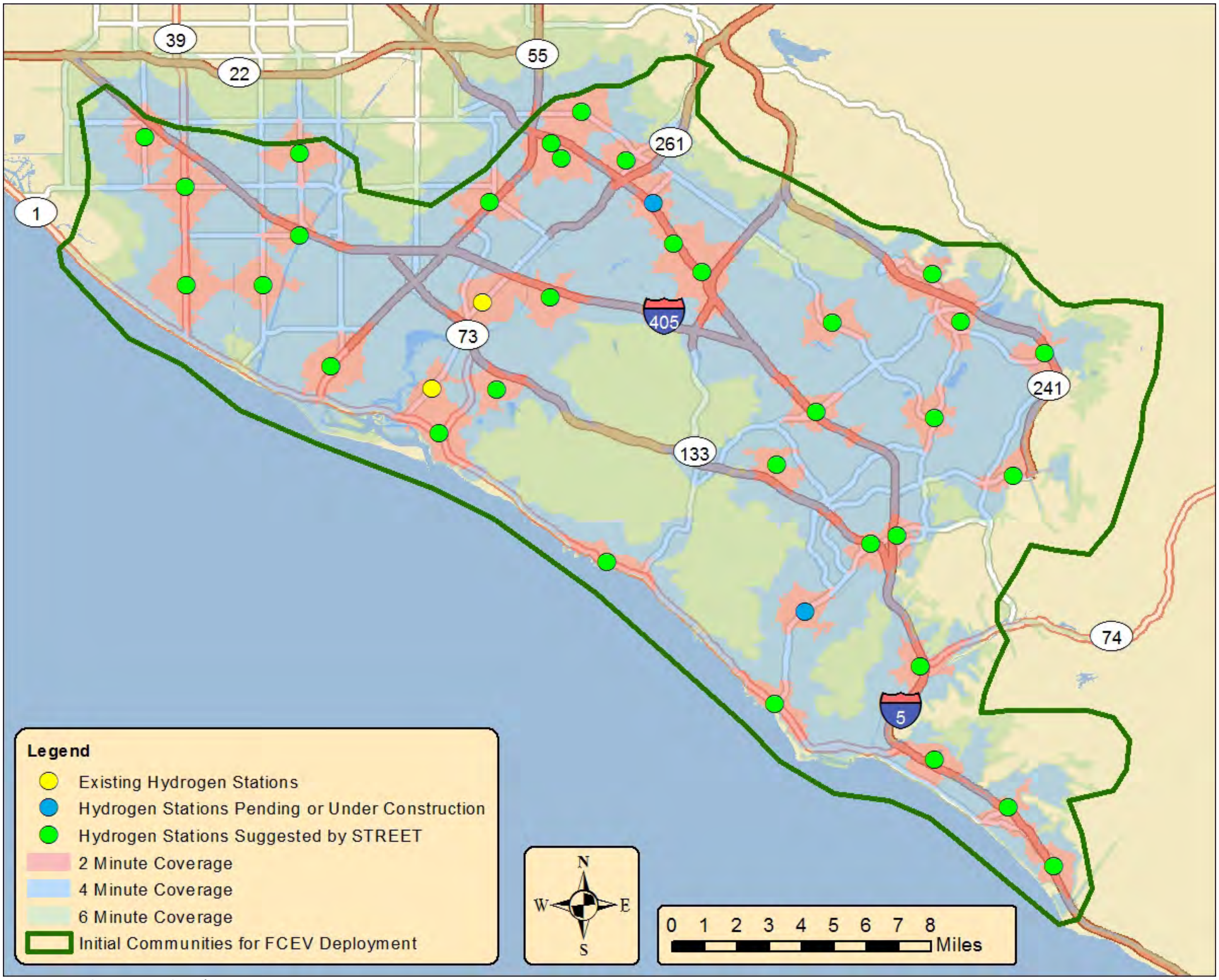
The Orange County region has two existing and two planned hydrogen stations located at the addresses listed in Table 9. An additional 33 stations, for a total of 37, are proposed by the analysis herein to complete a regional network with service coverage comparable to the existing 279 gasoline stations (13.3 percent). Figure 45 shows location and service coverage of the proposed Orange County region hydrogen station network.

Table 9: Location of Existing and Planned Stations in the Orange County Region

Location	Status	Capacity
1600 Jamboree Road, Newport Beach, CA 92660	Operational	100 kg/day
19172 Jamboree Road, Irvine, CA 92612	Pending/Operational at 25 kg/day capacity	180 kg/day
4162 Trabuco Road, Irvine, CA 92620	Pending	180 kg/day
26572 Junipero Serra Road, San Juan Capistrano, CA 92675	Pending	240 kg/day

Source: UC Irvine

Figure 45: Existing, Planned, and Suggested Hydrogen Stations in the Orange County Region Required to Provide the Same Level of Service as the Existing Gasoline Stations



Source: UC Irvine

San Francisco Bay Area Regions

As outlined previously, two major regions of the San Francisco Bay area have been selected as initial market regions. Detailed station placement optimization within these regions can produce a level of service for fuel cell electric vehicle customers equivalent to that of existing gasoline stations, with significantly fewer station locations.

Berkeley Region

The Berkeley region has one existing hydrogen station located at the address shown in Table 10. An additional 10 stations, for a total of 11, are proposed by the analysis herein to complete a regional network with service coverage comparable to the existing 75 gasoline stations (14.7

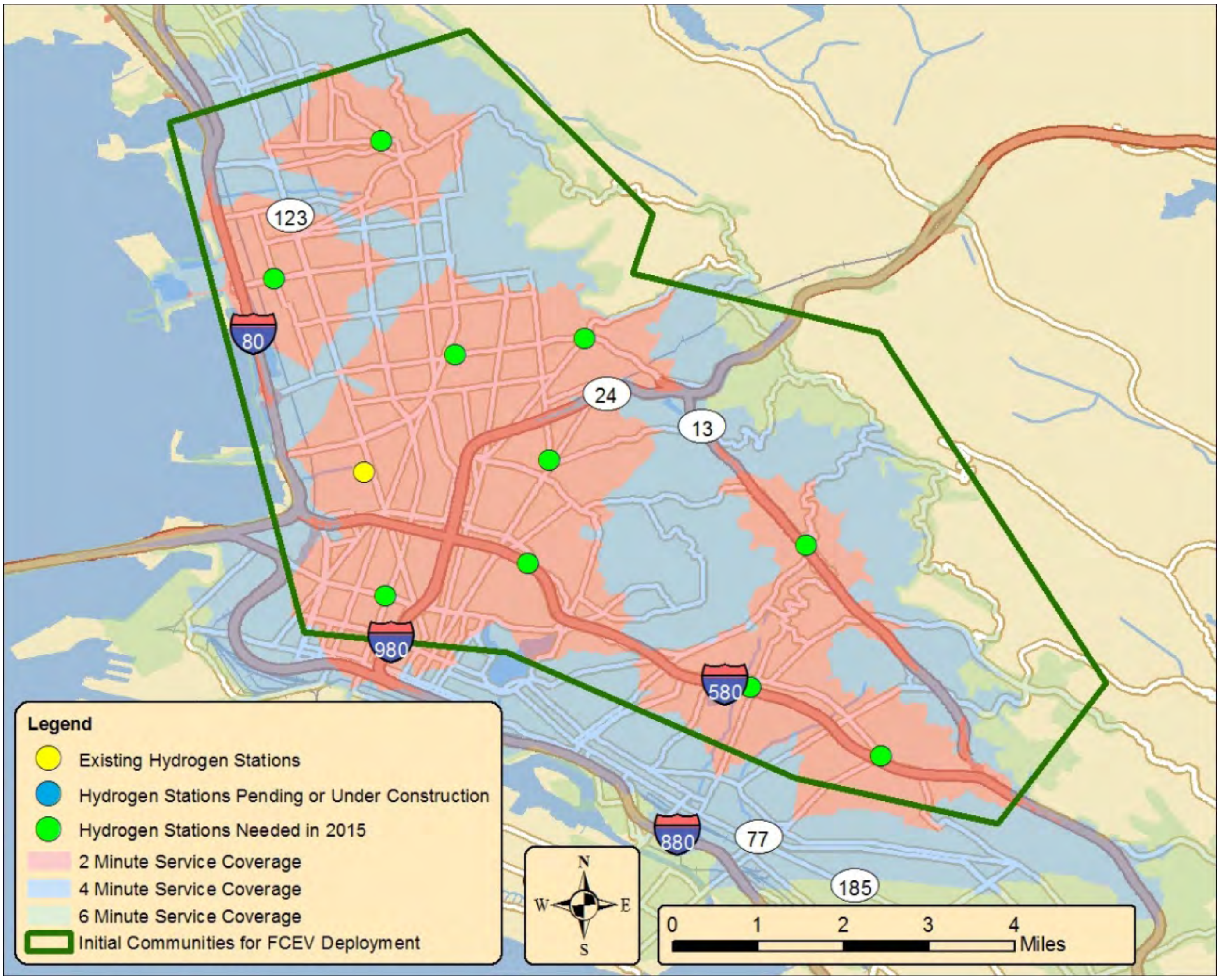
percent). Figure 46 shows location and service coverage of the proposed Berkeley region hydrogen station network.

Table 10: Location of the Existing Hydrogen Stations in the Berkeley Region

Location	Status	Capacity
1172 45th St., Emeryville, CA 94608	Pending	425 kg/day (mixed car and bus)

Source: UC Irvine

Figure 46: Existing, Planned, and Suggested Hydrogen Stations in the Berkeley Region Required to Provide the Same Level of Service as the Existing Gasoline Station Infrastructure in the Region

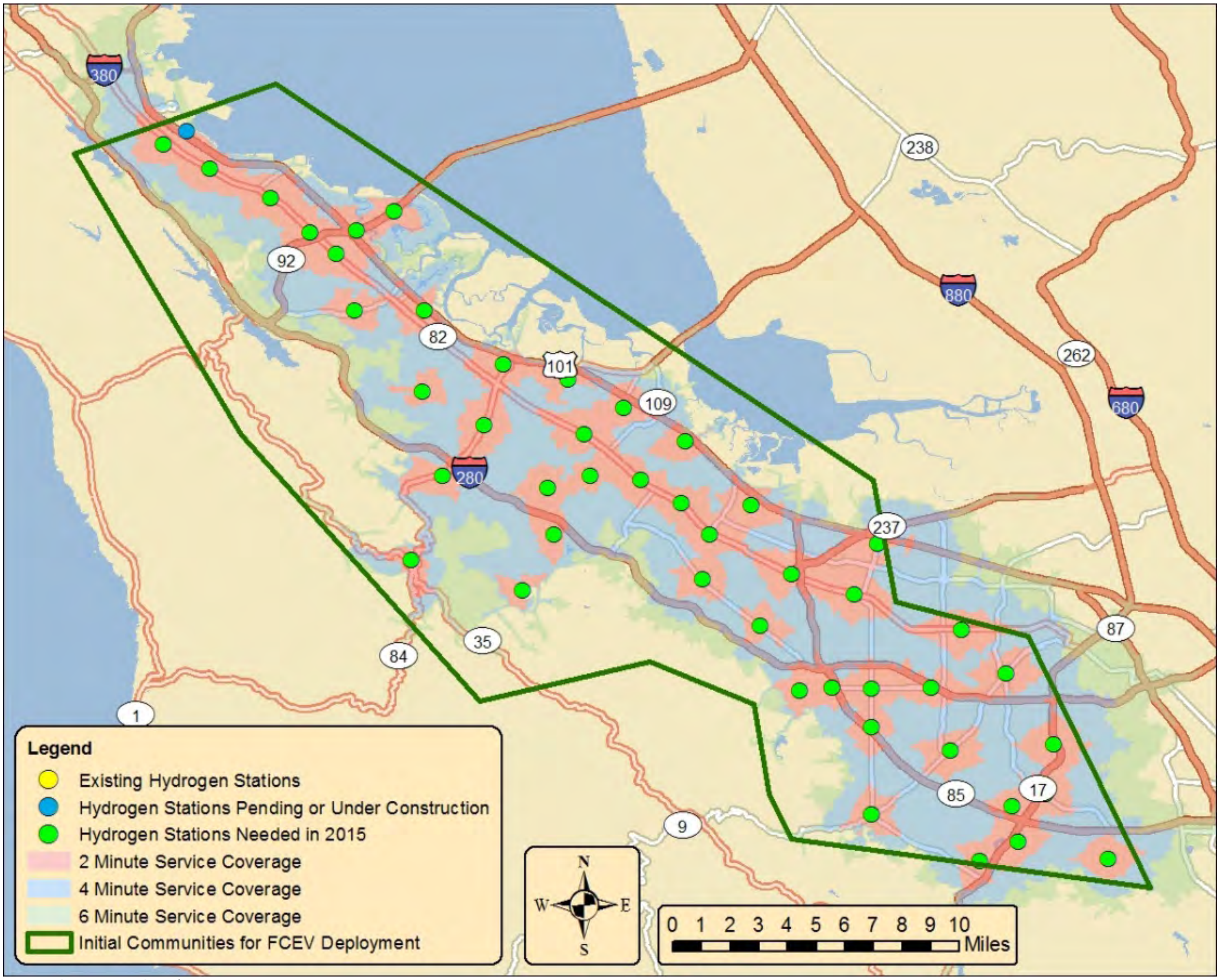


Source: UC Irvine

South Bay Region

The South Bay region has one planned hydrogen station. Funding has been allocated, but the specific South Bay location has yet to be determined. A station located at the San Francisco International Airport is used herein as a placeholder for mapping and optimization purposes. An additional 46 stations, for a total of 47, are proposed by the analysis herein to complete a regional network with service coverage comparable to the existing 215 gasoline stations (21.8 percent). Figure 47 shows location and service coverage of the proposed South Bay region hydrogen station network.

Figure 47: Existing, Planned, and Suggested Hydrogen Stations in the South Bay Region Required to Provide the Same Level of Service as the Existing Gasoline Station Infrastructure in the Region



Source: UC Irvine

CHAPTER 5: Hydrogen Station Network Required for Early Commercialization

The previous results for each optimized geographic region indicate that the level of existing gasoline station coverage can be duplicated through well-placed location optimization with only 13-21 percent as many outlets. This conclusion is extremely encouraging for the development of a new fueling infrastructure; the established paradigm need not be fully duplicated. This conclusion also approximates the experience reported in the literature with regard to the availability of diesel fueling stations, whereby a network having 10 percent as many outlets as the existing gasoline station network served to address fuel availability concerns for potential consumers [17].

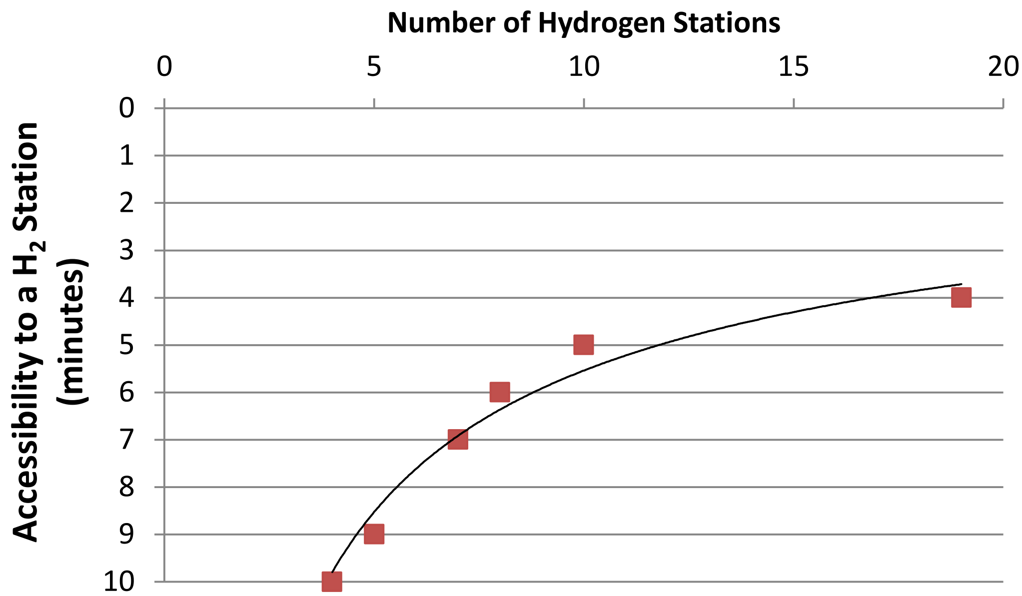
However, most consumers recognize that the adoption of new technology may require some level of compromise in standard service, and that the ubiquitous gasoline refueling infrastructure may be more than that required. Sperling and Kitamura characterize gasoline infrastructure as “overbuilt” [17]. For example, the common trend of gasoline stations located directly across the street from one another is due to a combination of competitive forces and capacity constraints. Neither of these conditions will likely be present in what is perceived to be the initial commercial launch of fuel cell electric vehicles.

Furthermore, some locations throughout California have significantly fewer gasoline stations on a per capita and per area basis than the state average. For example, Irvine has just 1.57 stations per 10,000 residents compared to 2.59 stations per 10,000 residents in Santa Monica. Likewise, Irvine has just 0.42 stations per square mile compared to 2.55 in Santa Monica. This result indicates that the acceptable number of stations is generally considerably lower than those actually installed.

Six-Minute Coverage Is Optimum Compromise

The station location optimization method provided by the STREET tool allows for the calculation of maximum travel time for each additional hydrogen station added to a network. For example, the current existing and planned hydrogen stations in the Santa Monica region (four total) provide a maximum travel time from anywhere in the region to a hydrogen station in 10 minutes. The addition of just one more station (five total) can drop this travel time down to 9 minutes. Two more stations (seven total) reduce the time to 7 minutes, and an additional station (eight total) reduces the travel time to 6 minutes. Two more (10 total) can reach coverage in just 5 minutes, and a final 9 additional stations (19 total) are required to reach 4-minute travel time in parity with the 126 existing gasoline stations. This trend is shown in Figure 48.

Figure 48: Decrease in Maximum Travel Time to a Hydrogen Station in the Santa Monica Region With Increasing Numbers of Stations



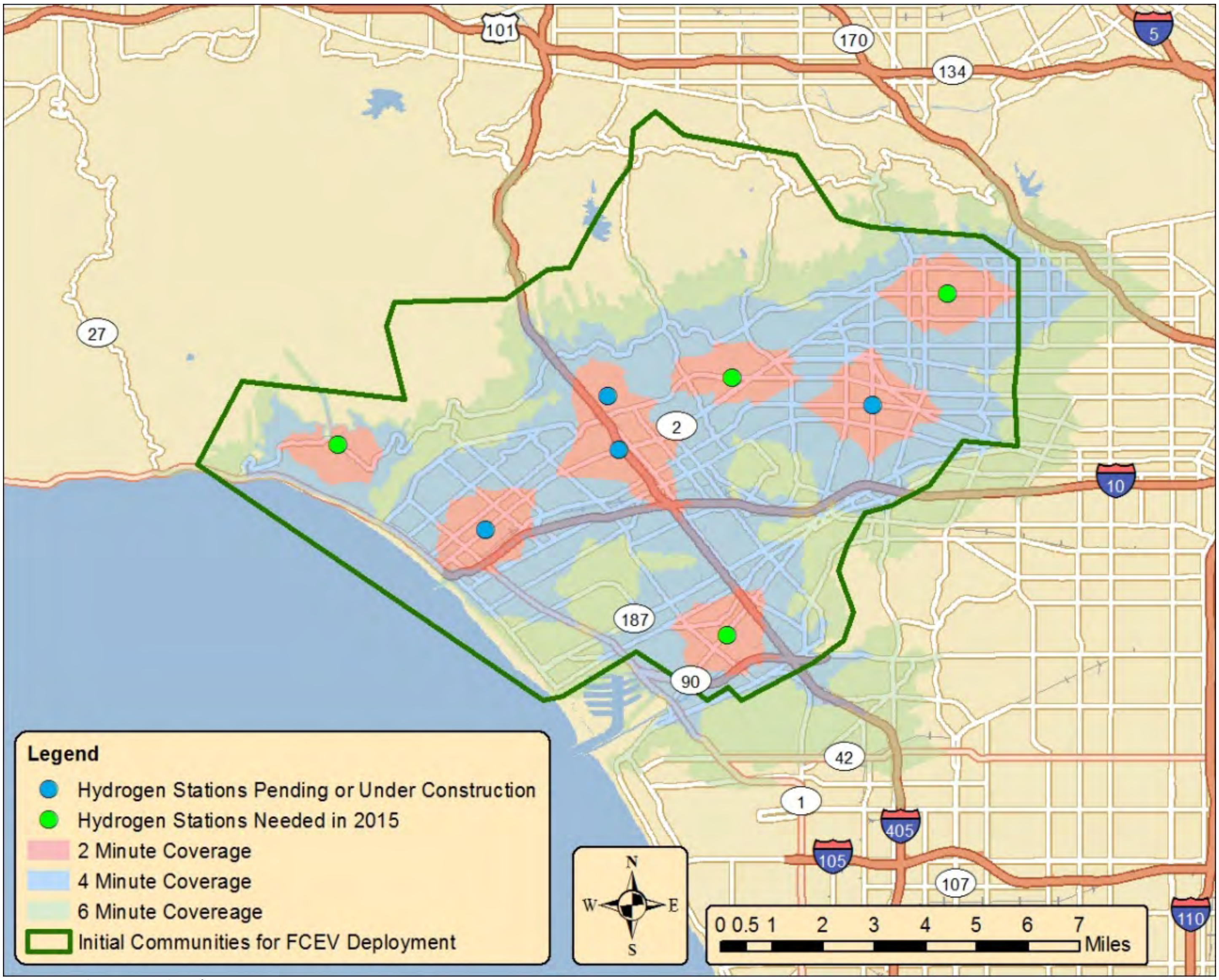
Source: UC Irvine

On examination of Figure 48, service coverage of 6 minutes appears to be a good compromise between parity with gasoline and minimization of infrastructure investment. With 126 existing gasoline stations in the Santa Monica region, 8 hydrogen stations represent just 6.3 percent of the total. This result matches well with previous research in the field of fueling infrastructure, which indicates that 5 percent of gasoline fueling locations require alternative fuel to alleviate driver concerns about fuel availability [14][15]. Previous research also indicates that high-traffic-volume roadway and residential areas are priorities, and that simply applying a blanket percentage of stations is insufficient; optimization of locations must be rigorous to achieve a viable network with single-digit percentages of stations.

Results by Region

A 6-minute travel time compromise can be achieved in all fuel cell electric vehicle market regions. Figure 49 shows four existing and planned stations, plus an additional four stations required to provide 6-minute coverage in the Santa Monica region. As shown by the contour plots representing travel times, the eight stations cover most areas within 4 minutes and nearly everywhere within 6 minutes.

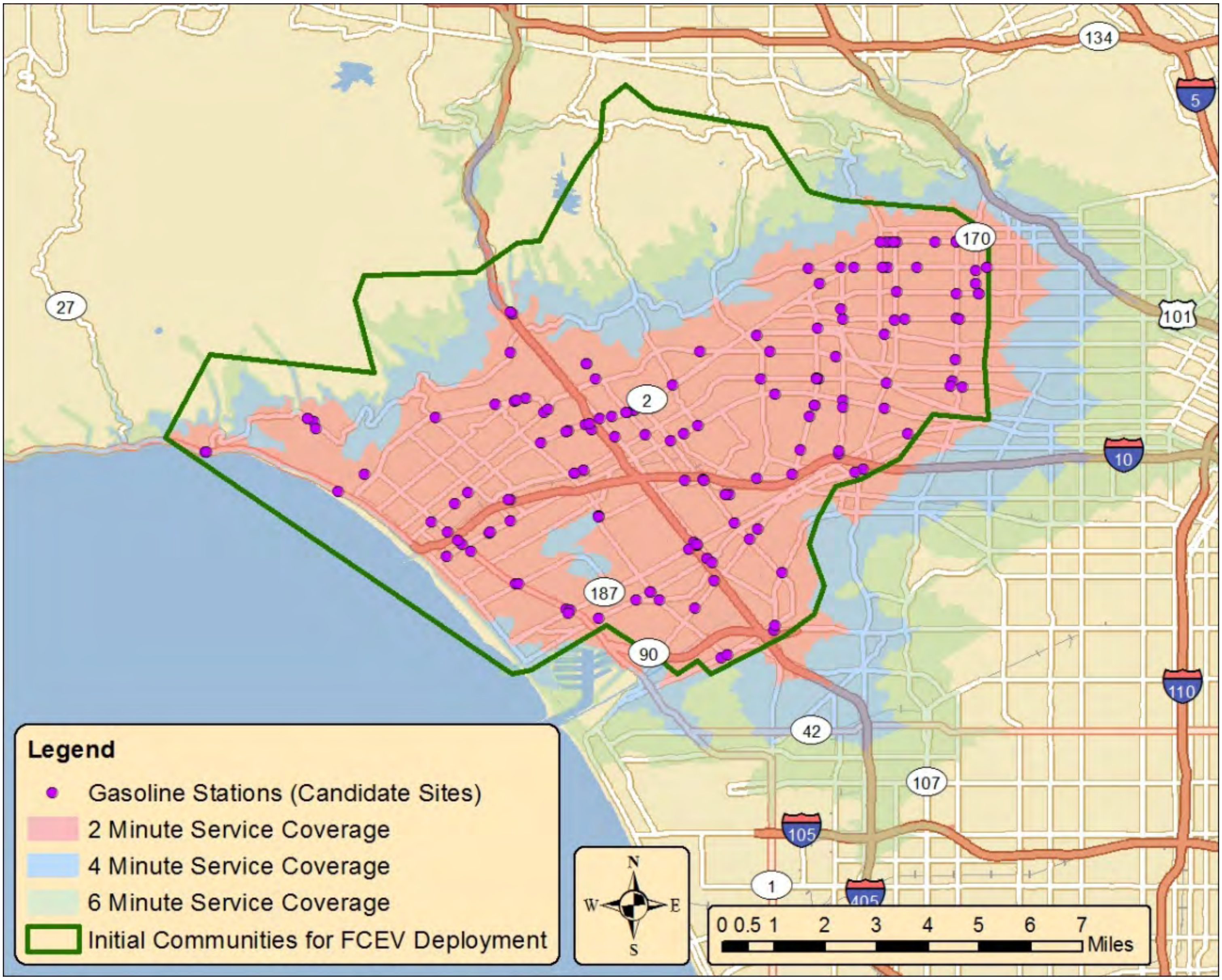
Figure 49: Eight Hydrogen Stations Required in the Santa Monica Region to Achieve a Maximum Travel Time of Less Than 6 Minutes



Source: UC Irvine

The northern areas within the Santa Monica region that are not within 6 minutes of a hydrogen station are relatively isolated, sparsely populated areas that are also not within 6 minutes driving distance of a gasoline stations, as shown in Figure 50.

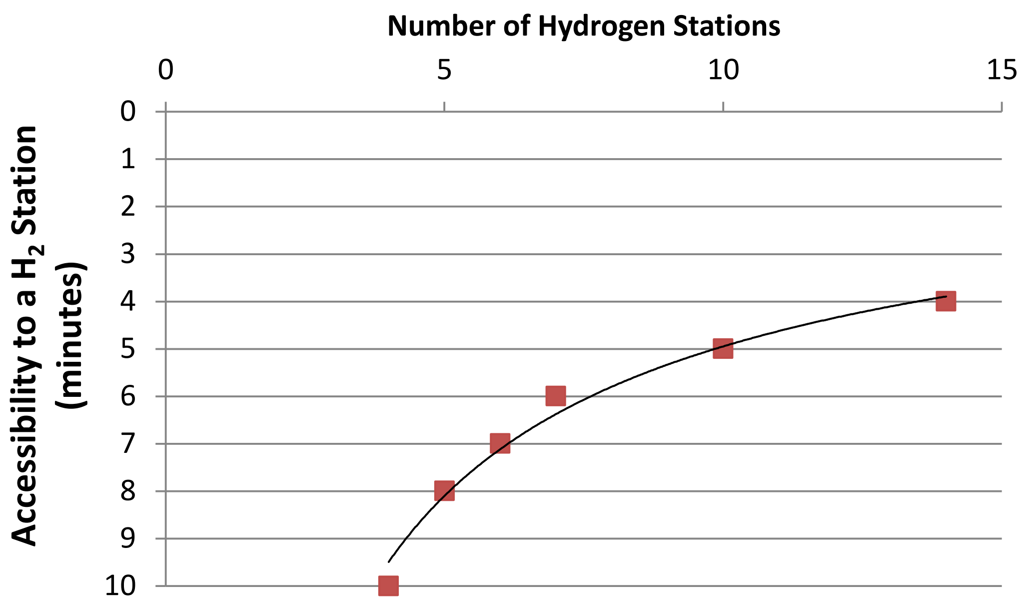
Figure 50: Service Coverage of the 126 Gasoline Stations in the Santa Monica Region Showing That Not All Areas Are Well-Covered



Source: UC Irvine

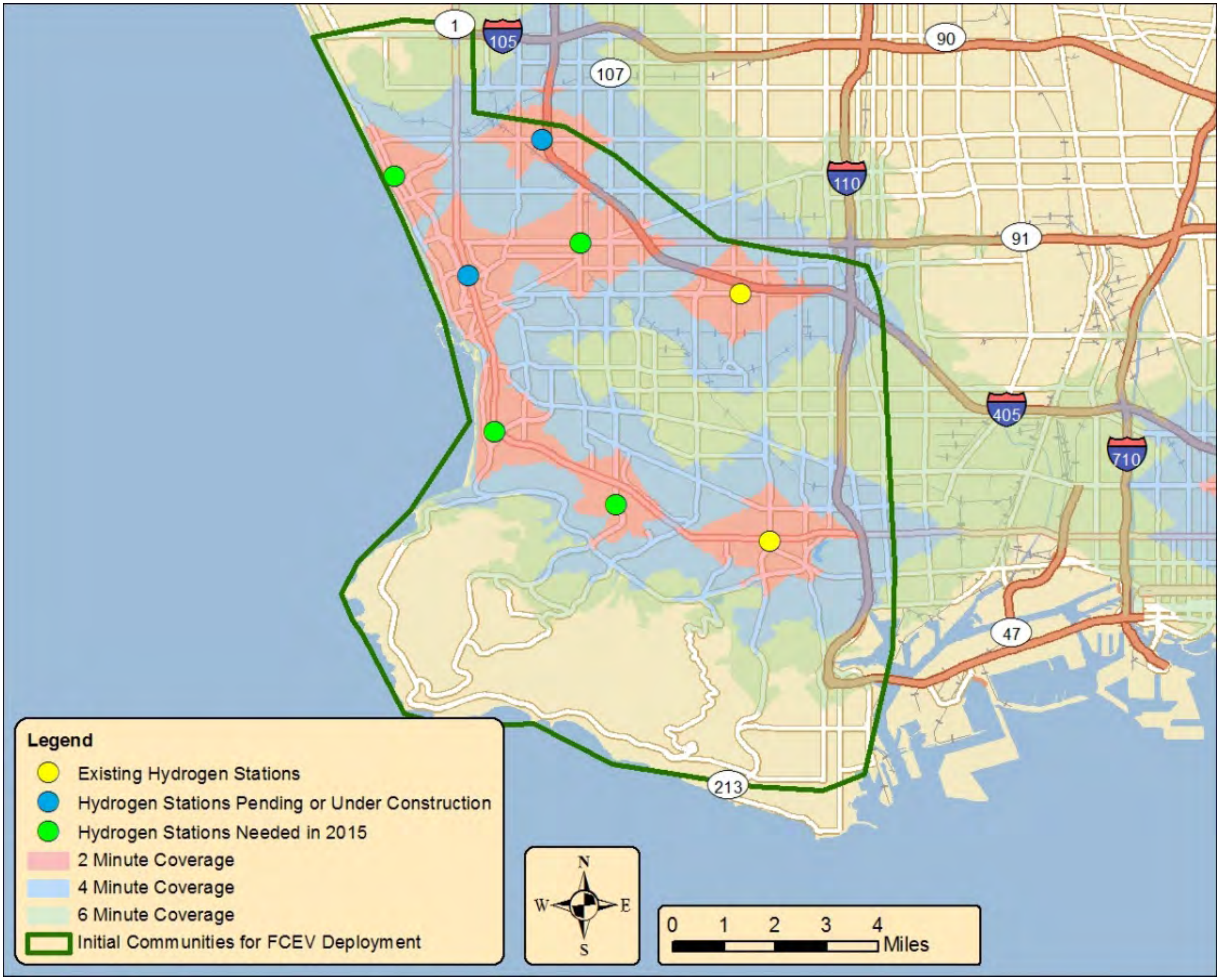
Figure 51 shows a plot of maximum travel time versus number of hydrogen stations in the Torrance region. Six-minute travel time can be achieved with just eight stations placed, as shown in Figure 52. As shown by the contour plots representing travel times, the eight stations cover most areas within 4 minutes and nearly everywhere within 6 minutes. As in the Santa Monica region, the southern portions of the Torrance region that are not well-covered by hydrogen stations are also not well-covered by the current gasoline infrastructure due to geography and population.

Figure 51: Station Number Versus Maximum Travel Time in the Torrance Region



Source: UC Irvine

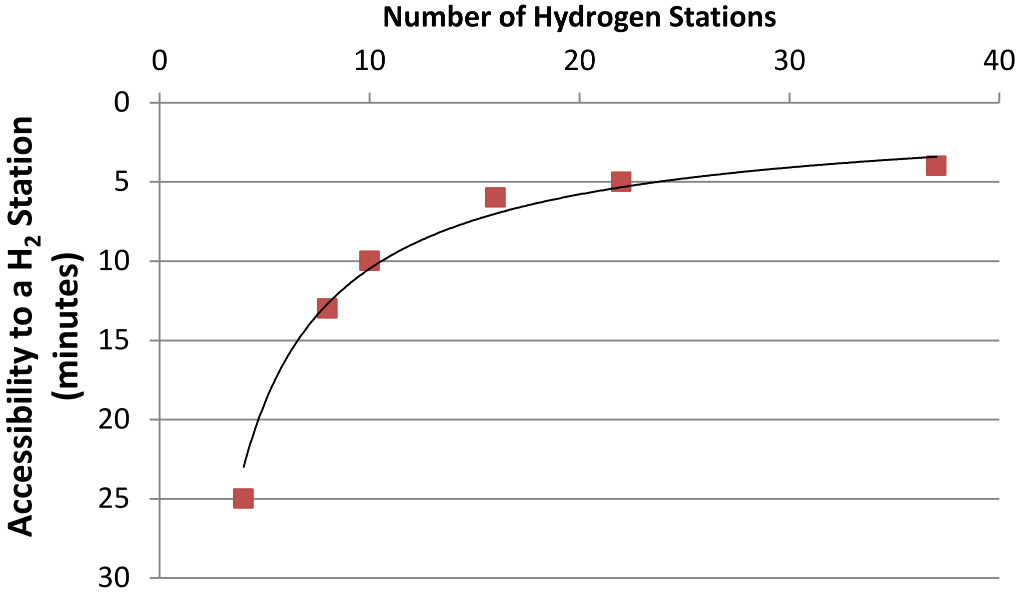
Figure 52: Eight Hydrogen Stations Required in the Torrance Region to Achieve a Maximum Travel Time of Less Than 6 Minutes



Source: UC Irvine

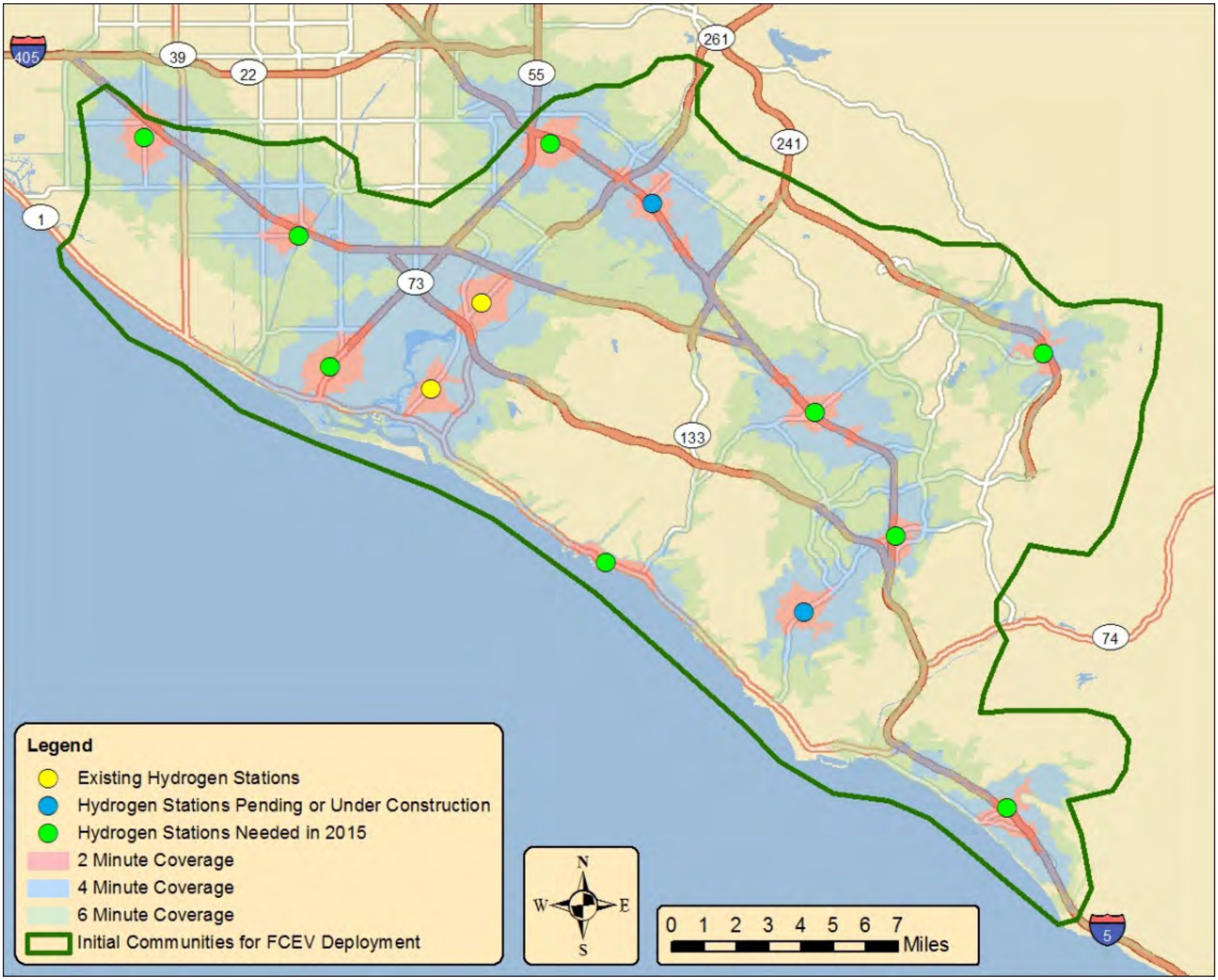
Figure 53 shows a plot of maximum travel time versus number of hydrogen stations in the Orange County region. Six-minute travel time can be achieved with just 13 stations placed as shown in Figure 54. Again, most areas are covered within 4 minutes, nearly all are covered within 6 minutes, and those areas that are not well-covered are low-population areas that are correspondingly not well-covered by existing gasoline stations.

Figure 53: Station Number Versus Maximum Travel Time in the Orange County Region



Source: UC Irvine

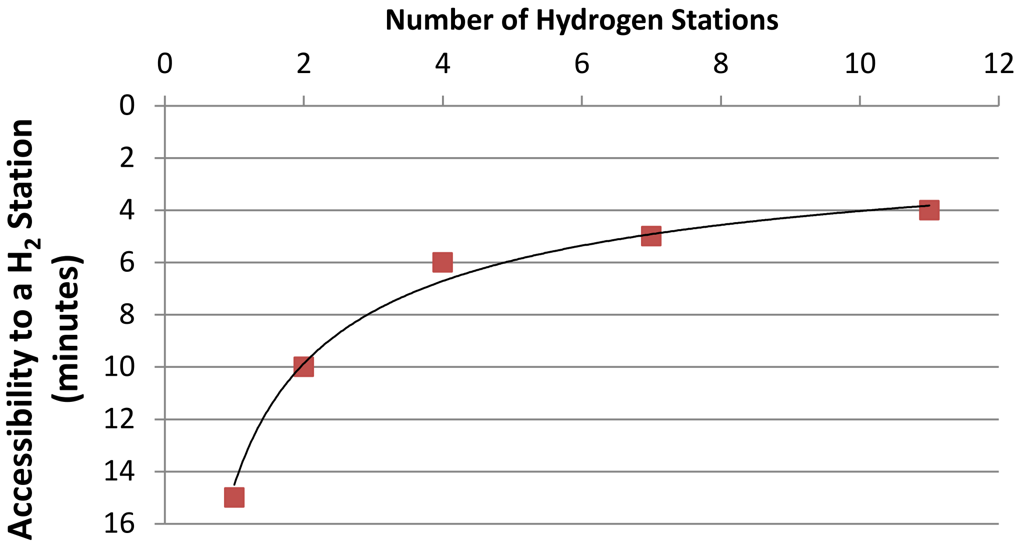
Figure 54: Thirteen Hydrogen Stations Required in the Orange County Region to Achieve a Maximum Travel Time of Less Than 6 Minutes



Source: UC Irvine

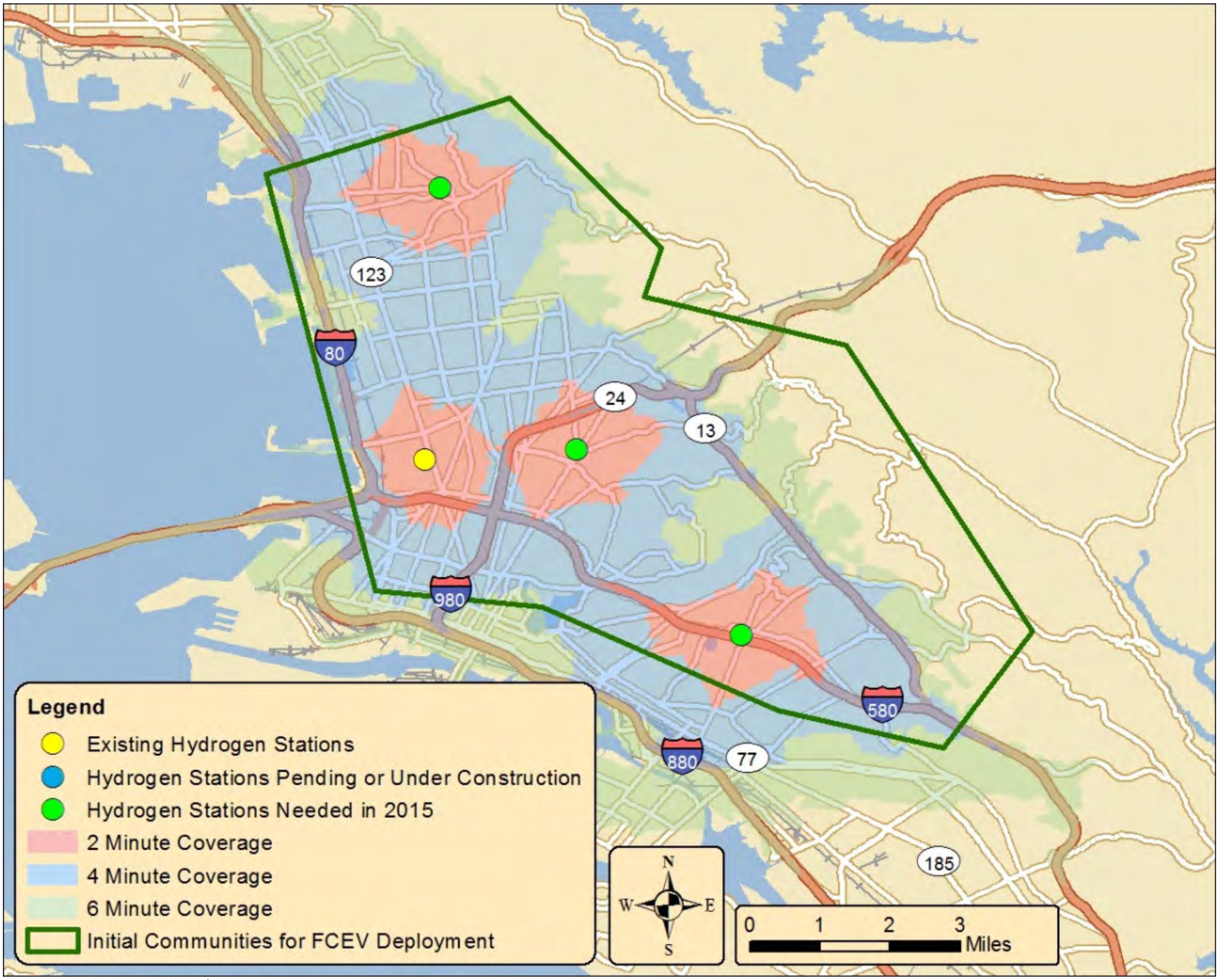
Figure 55 shows a plot of maximum travel time versus number of hydrogen stations in the Berkeley region. Six-minute travel time can be achieved with just four stations placed as shown in Figure 56.

Figure 55: Station Number Versus Maximum Travel Time in the Berkeley Region



Source: UC Irvine

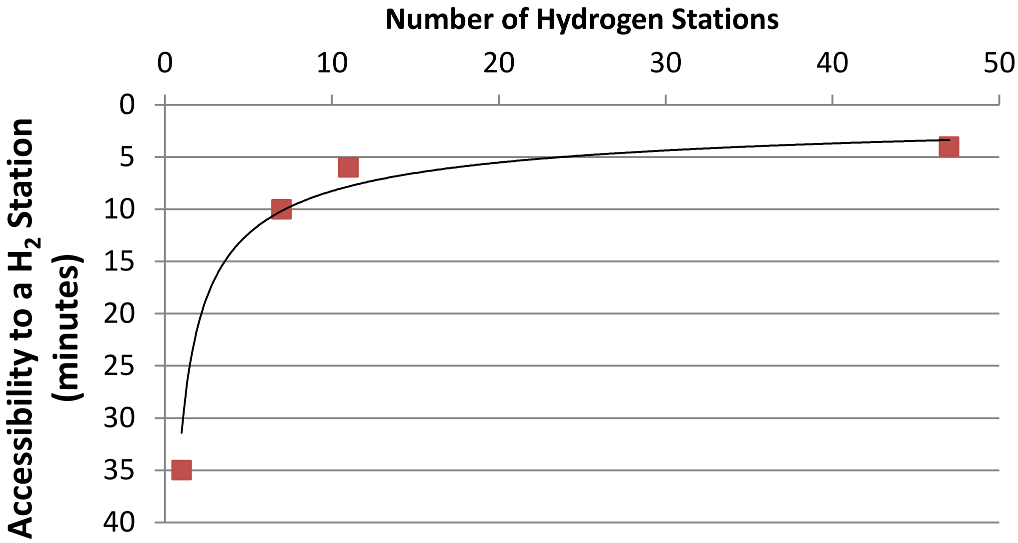
Figure 56: Four Hydrogen Stations Required in the Berkeley Region to Achieve a Maximum Travel Time of Less Than 6 Minutes



Source: UC Irvine

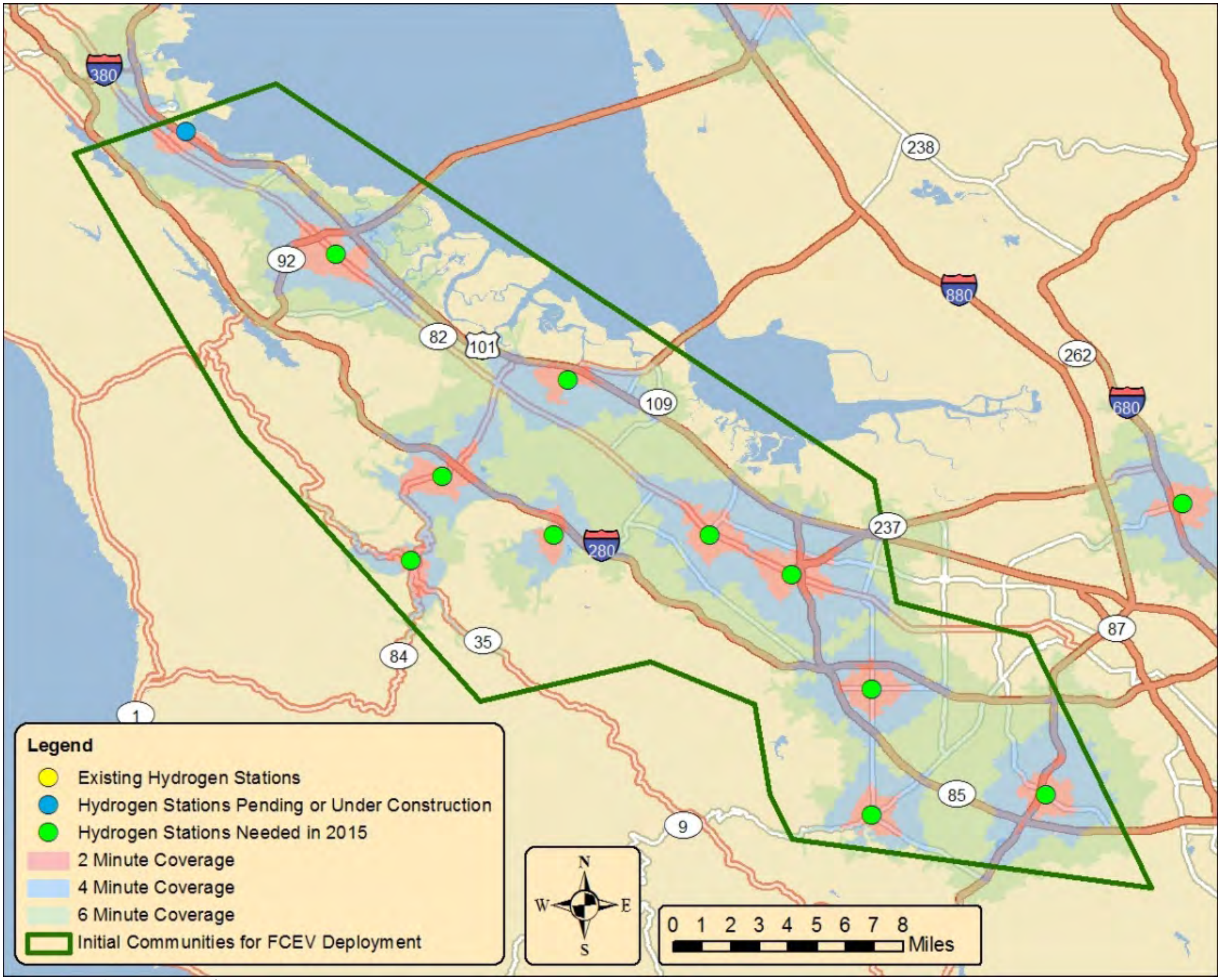
Figure 57 shows a plot of maximum travel time versus number of hydrogen stations in the South Bay region. Six-minute travel time can be achieved with just 12 stations placed as shown in Figure 58.

Figure 57: Station Number Versus Maximum Travel Time in the South Bay Region



Source: UC Irvine

Figure 58: Twelve Hydrogen Stations Required in the South Bay Region to Achieve a Maximum Travel Time of Less Than 6 Minutes



Source: UC Irvine

Connector and Destination Stations Are Required

Provision of fuel for long-distance trips is essential to meet customer expectations [14]. By limiting the fueling network for fuel cell electric vehicles, the long-distance capabilities of these vehicles are eliminated, thus forcing fuel cell electric vehicles to compete in the same market as other limited-range alternative fuel vehicles, instead of competing directly with gasoline vehicles.

The additional hydrogen stations within each target region required to begin merging the clusters into a regional network are identified based on a combination of household income, population, and cars per household.

Finally, hydrogen stations needed to provide connectivity from a target region to typical destinations are identified based on an understanding of where drivers in the target regions typically drive for vacations, excursions, or business.

Significant automaker input was used throughout this work, but automaker insight was the main contributor to the determination of connector and destination station locations. Table 11 lists the existing, planned, and proposed hydrogen stations.

Table 11: List of Existing, Planned, and Proposed Hydrogen Stations as of March 2012

Region	Existing or Planned H_2 Stations	Additional H_2 Stations Recommended	Total H_2 Stations Recommended
Robust network of hydrogen stations in cluster areas			
Santa Monica/West LA	4	4	8
Torrance	4	4	8
Orange County	4	9	13
Berkeley	1	3	4
South SF Bay	1	11	12
Clusters begin to merge into a regional network of hydrogen stations			
Burbank	1	0	1
San Fernando Valley	0	1	1
Pasadena	0	2	2
Anaheim	0	1	1
Long Beach	0	1	1
Downtown San Francisco	0	2	2
Pleasanton	0	1	1
Hayward	0	1	1
Sacramento	1	1	2
Riverside	0	1	1
Diamond Bar	1	0	1
Los Angeles (CSULA)	1	0	1
Destination and connector hydrogen stations			
La Jolla/Del Mar/San Diego	0	2	2
Santa Barbara	0	1	1
Palm Springs	0	1	1
I-5 Corridor	0	1	1
Sonoma	0	1	1
Napa	0	1	1
Lake Tahoe	0	1	1
Total	18	50	68

Source: UC Irvine

CHAPTER 6: Optimum Station Network Increases Throughput

CaFCP Survey Results

The California Fuel Cell Partnership conducted a blind survey of automaker member fuel cell electric vehicle deployment plans in January 2011. Participants included Toyota, Honda, Mercedes-Benz, Hyundai/Kia, General Motors, Nissan, and Volkswagen. The results of this survey are provided in Table 12, showing that the number of deployed vehicles increases moderately from 2011 until 2015, at which point the initial commercialization of fuel cell electric vehicles produces dramatic increases in deployed vehicle numbers.

Table 12: Results of 2011 CaFCP Automaker Deployment Plan Survey

Region	Total H_2 Stations Recommended	FCV Deployment Numbers			
		2012	2013	2014	2015-2017
Santa Monica/West LA	8	240	347	1,161	34,230
Torrance	8				
Orange County	13				
San Fernando Valley	2				
Pasadena	2				
Anaheim	1				
Long Beach	1				
Riverside	1				
Diamond Bar	1				
Los Angeles (CSULA)	1				
Berkeley	4	39	50	144	14,500
South SF Bay	12				
Downtown SF	2				
Pleasanton	1				
Hayward	1				
Sacramento	2	22	25	48	1,730
La Jolla/Del Mar	2	7	3	29	1,725
Santa Barbara	1	3	4	6	405
Palm Springs	1				100
Harris Ranch	1	1	1	1	310
Sonoma	1	1	1	1	310
Napa	1	1	1	1	310
Lake Tahoe	1				
Total	68	312	430	1,389	53,000

Source: UC Irvine

Average Throughput per Station

Given the detailed plan of hydrogen stations required for early commercialization outlined in combination with the yearly vehicle projections provided by the CaFCP, simple averaging can be used to estimate the amount of hydrogen dispensed at each station per day. Using the 0.7 kilogram (kg) of hydrogen required per fuel cell electric vehicle per day [9], Table 13 shows the average amount of hydrogen required at stations in each region for the 2015-2017 time frame vehicle numbers.

Table 13: Average Station Throughput for Each Region in 2017

Region	Total H_2 Stations Recommended	2015-2017 Average Throughput
Santa Monica/West LA	8	630 kg/day
Torrance	8	
Orange County	13	
San Fernando Valley	2	
Pasadena	2	
Anaheim	1	
Long Beach	1	
Riverside	1	
Diamond Bar	1	
Los Angeles (CSULA)	1	
Berkeley	4	500 kg/day
South SF Bay	12	
Downtown SF	2	
Pleasanton	1	
Hayward	1	
Sacramento	2	600 kg/day
La Jolla/Del Mar	2	600 kg/day
Santa Barbara	1	280 kg/day
Palm Springs	1	70 kg/day
Harris Ranch	1	55 kg/day
Sonoma	1	
Napa	1	
Lake Tahoe	1	
Total	68	31,710 kg/day

Source: UC Irvine

Undoubtedly, station throughput will vary within each region and between regions. For example, it is unlikely that a bridging station located between Los Angeles and San Francisco will experience the same level of usage as a station in the midst of a strong market region. However, it is obvious from the numbers in Table 13 that if infrastructure is optimized for efficient coverage while limited to only what is absolutely necessary, the daily per-station hydrogen throughput could be substantial by 2017. As a result, the economics of hydrogen station operation and the price of hydrogen fuel can be more favorable to operators and consumers, respectively, than many previous studies have concluded [8][10].

CHAPTER 7: Summary

Early fuel cell electric vehicle markets span wide portions of California, centered in denser urban regions. Careful optimization in the most promising market regions can replicate the level of coverage provided by existing gasoline infrastructure by colocating hydrogen fueling at just 10-13 percent of gasoline locations. However, the level of coverage required for initial commercialization does not need to identically match gasoline infrastructure. As a result, a 6-minute maximum travel time strikes a good compromise between high capital expenditures required to match the 4-minute coverage time for gasoline stations and the necessary infrastructure to enable an early market. This level of coverage requires hydrogen to be colocated at just 5-7 percent of existing gasoline stations. In addition to denser infrastructure requirements in the strongest potential markets, additional stations are required to connect market regions, nucleate emerging markets and to allow driving throughout major destinations in the state. In all, 68 operational stations will be required to initiate fuel cell electric vehicle commercialization in numerous California markets.

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ACRONYMS

ABAG	Associated Bay Area Governments
AFV	alternative fuel vehicle
APEP	Advanced Power and Energy Program
ARVT/ARFVTP	Alternative and Renewable Fuels and Vehicle Technology Program
ATSM	American Society for Testing and Materials
CaFCP	California Fuel Cell Partnership
CAM	Commission Agreement Manager
CCR	California Code of Regulations
CEQA	California Environmental Quality Act
FCEV	fuel cell electric vehicles
GHG	greenhouse gas
GIS	Geographic information systems
MPH	miles per hour
OCTAM	Orange County Transportation Analysis Model
STREET	Spatially and Temporally Resolved Energy and Environment Tool
U.S. EPA	United States Environmental Protection Agency