Title
Hydrogen Infrastructure Requirements for Zero-Emission Freight Applications in California

Authors
Li, Guozhen, PhD
Ogden, Joan, PhD
Miller, Marshall, PhD

Publication Date
2021-03-01

DOI
10.7922/G2N8782T

Hydrogen Infrastructure Requirements for Zero-Emission Freight Applications in California

A Research Report from the University of California Institute of Transportation Studies

Guozhen Li, Graduate Student Researcher, Transportation Technology and Policy, University of California, Davis

Joan Ogden, Professor Emerita, Environmental Science and Policy, University of California, Davis

Marshall Miller, Senior Development Engineer, Institute of Transportation Studies, University of California, Davis

March 2021

REPORT No.: UC-ITS-2018-22 | DOI:10.7922/G2N8782T

Technical Report Documentation Page

1. Report No.
UC-ITS-2018-22

2. Government Accession No.
N/A

3. Recipient's Catalog No.
N/A

4. Title and Subtitle
Hydrogen Infrastructure Requirements for Zero-Emission Freight Applications in California

5. Report Date
March 2021

6. Performing Organization Code
ITS-Davis

7. Author(s)
Guozhen Li, Ph.D.
Joan Ogden, Ph.D. https://orcid.org/0000-0002-2776-9130
Marshall Miller, Ph.D. https://orcid.org/0000-0002-9105-3188

8. Performing Organization Report No.
UCD-ITS-RR-21-16

9. Performing Organization Name and Address
Institute of Transportation Studies, Davis
1605 Tilia Street
Davis, Ca 95616

10. Work Unit No.
N/A

11. Contract or Grant No.
UC-ITS-2018-22

12. Sponsoring Agency Name and Address
The University of California Institute of Transportation Studies
www.ucits.org

13. Type of Report and Period Covered
Final Report (January 2018 – December 2018)

14. Sponsoring Agency Code
UC ITS

15. Supplementary Notes
DOI:10.7922/G2N8782T

16. Abstract

Zero-emission vehicles are seen as key technologies for reducing freight- related air pollution and greenhouse gas emissions. California's 2016 Sustainable Freight Action Plan established a target of 100,000 zero-emission freight vehicles utilizing renewable fuels by 2030. Hydrogen fuel cell vehicles are a promising zero-emission technology, especially for applications where batteries might be difficult to implement, such as heavy-duty trucks, rail, shipping and aviation. However, California's current hydrogen infrastructure is sparse, with about 25 stations, primarily sited to serve fuel cell passenger vehicles and buses. New infrastructure strategies will be critical for implementing hydrogen freight applications. The researchers analyzed hydrogen infrastructure requirements, focusing on hydrogen fuel cells in freight applications, using a California-specific EXCEL-based scenario model developed under the Sustainable Transportation Energy Pathways program (STEPS) at the Institute of Transportation Studies at UC Davis (Miller et al, 2017). Hydrogen vehicle adoption and demand was estimated for trucks, rail, shipping, and aviation, for a range of scenarios out to 2050.

17. Key Words
Zero emission vehicles, hydrogen fuels, fuel cells, freight transportation, heavy duty trucks, service stations, demand, mathematical models

18. Distribution Statement
No restrictions.

19. Security Classification (of this report)
Unclassified

20. Security Classification (of this page)
Unclassified

21. No. of Pages
32

21. Price
N/A

Form Dot F 1700.7 (8-72)

Reproduction of completed page authorized

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

Acknowledgments

This study was made possible through funding received by the University of California Institute of Transportation Studies from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project.

Disclaimer

Table of Contents

List of Tables

List of Figures

Executive Summary

State transportation plans in California highlight the need for zero-emission vehicles in medium- and heavy-duty transportation, including freight transport and public transit. Hydrogen fuel cell vehicles (FCEVs) are a promising zero emission technology, especially for applications where batteries might be difficult to implement. However, California's hydrogen infrastructure to date is sparse, with about 30 stations, primarily sited to serve fuel cell cars and buses. New infrastructure strategies will be critical for implementing hydrogen freight applications. This study focuses on the hydrogen fuel demand and refueling infrastructure need from medium- and heavy-duty (MD/HD) FCEVs in California. Two distinctive segments of the MD/HD FCEV market—local return-to-base market and long-haul market—are studied using suitable approaches respectively. For the local FCEV market, we compile a dataset of potential FCEV fleets, and develop a modeling tool that calculates vehicle stock turnover, allocates FCEV population across geographic locations, and estimate hydrogen fuel demands over time. For the long-haul FCEV market, we identify major freight transport routes in California and turn them into a network graph model, based on which we use mathematical programming to find optimal hydrogen refueling station layouts that meet refueling needs from intra-California long-haul trips, while minimizing the number of stations required.

The demand for hydrogen fuel from MD/HD FCEVs is heavily concentrated in California's two biggest metropolitan areas, Los Angeles and San Francisco Bay area. Two additional high demand regions include Stockton and Sacramento. These demand centers are largely driven by the locations of ports and major freight corridors. Industrial parks and bus fleet hubs are also important generators of hydrogen demand.

The location optimization model finds 131 refueling station sites to serve the local FCEVs. Station with sizes between 1,000 and 5,000 kgH2/day are the most common in our 2030 scenario. Extremely large stations over 20,000 kgH2/day often appear near ports, which is consistent with our aggressive targets about drayage truck population. A hydrogen refueling network for long-haul fuel cell trucks based on the optimization model consists of 13 stations spread across the state. Overall, hundreds of metric tons of daily hydrogen supply is needed by 2030 to support the local hydrogen fleets, and the refueling points vary by size, from 1,000 kg per day to nearly 50,000 kg per day.

Introduction

Recent state transportation plans in California highlight the need for sustainable freight technologies and fuels. Zero emission vehicles are key technologies for reducing freight-related air pollutant and greenhouse gas emissions. California's 2016 Sustainable Freight Action Plan proposed a target of 100,000 zero emission freight vehicles by 2030 including forklifts, utilizing renewable fuels [1].

Fuel cell electric vehicle (FCEV) technology is an attractive zero-emission option in the medium and heavy-duty transport sectors, because of its low maintenance, light weight and fast refueling. A fuel cell powertrain system has fewer moving parts than conventional internal combustion engine systems, thus reducing wear and tear, and consequently saves on maintenance costs [2]. Compared to battery electric vehicles (BEVs), fuel cell systems impose less weight and space penalty and can be refueled faster [3]. The potentially large weight penalty due to large batteries can significantly reduce profits due to lower payloads. In commercial operations, where vehicles are frequently used to near-full capacities and operators are sensitive to costs and time, FCEV is one of the most promising pathways towards zero-emission.

Medium and heavy-duty FCEVs, including buses and trucks, have been demonstrated and in several cases successfully operated. As of 2017, 26 fuel cell electric buses (FCEBs) are in service in the US, with Alameda-Contra Costa Transit (AC-Transit) operating the largest FCEB fleet of 13 vehicles [4]. Shipping companies like UPS and FedEx are experimenting with Class 6 fuel cell delivery trucks [5,6], and Toyota has demonstrated real-world operation of a heavy-duty fuel cell port drayage truck [7]. Nikola Motor has proposed a long-haul fuel cell truck model and is reported to start field tests in 2018 [8].

Refueling infrastructure is one of the top critical components of a hydrogen-powered MD/HD transport system. Currently, California's hydrogen refueling infrastructure is sparse, with about 30 stations (and projected to reach 60 by 2020), primarily sited to serve light-duty, passenger fuel cell cars. Medium and heavy-duty FCEVs will need refueling facilities not only of different technical specifications, but also different location choice and planning concerns. For example, hydrogen refueling infrastructure near ports, distribution centers, and goods movement corridors are highly desired by the potential MD/HD FCEV operators but not sufficiently considered in current hydrogen infrastructure plans.

Many previous studies on refueling infrastructure planning for hydrogen vehicles are found in the literature, although they predominantly focus on light-duty passenger FCEVs. One approach for hydrogen station siting is treating hydrogen demands as *points* and choosing refueling stations from a set of candidate sites, while minimizing the aggregated cost for refueling. This is also known as a p-median problem. Nicholas et al. [9] take this approach and studied the strategy of choosing subsets of existing gasoline stations as hydrogen stations, while minimizing the average driving time from home to the nearest hydrogen station for the general population. Lin et al. [10] expand the p-median approach to deal with motorists at random locations on a traffic network. The randomly appearing fuel demands are aggregated to a set of points, and then addressed as a p-median problem.

An alternative to the p-median formulation is a max/min cover formulation. In this approach, each candidate refueling site is associated a geographic area it covers, for example, the area within 5 minutes of driving. Then the question is either to cover the largest area with a given number of stations (max cover) or to cover a given area with the minimum number of stations (min cover). The STREET model by Stephens-Romero et al. [11] takes this approach to study the optimal hydrogen station layout for the city of Irvine, California.

One other approach of fueling station optimization is flow capturing, where hydrogen demand is treated as *flows* or *paths*, rather than points. Meeting a demand is achieved by intercepting that flow/path. This approach establishes a more realistic model for on-route fuel demand of FCEVs. Kuby et al. [12,13,14,15] developed the Flow Refueling Location Model (FRLM) that implemented several variants of the flow capturing model.

In addition to finding optimal locations with operations research techniques, some other studies attempt to identify areas of high refueling needs based on demographic and socioeconomic metrics. California Air Resource Board’s California Hydrogen Infrastructure Tool (CHIT) [16] weighs in financial indicators (e.g., income, car purchase spending), education (e.g., higher degrees), and green vehicle adoption trends (e.g., popularity of hybrid electric vehicles) to develop a market potential metric for every geographic location in California, and compares the demand potential with existing hydrogen station coverage to highlight demand-supply gaps. Similarly, National Renewable Energy Laboratory’s Scenario Evaluation and Regionalization Analysis (SERA) [17] model develops an early adopter metric (EAM) for every location across the US to examine the hydrogen demand potentials.

Despite the wide range of hydrogen station placement studies in the literature, few have focused on medium and heavy-duty sectors. FCEV technology has been first tested and commercialized on light-duty passenger vehicles, and more stakeholders are beginning to realize the benefits it can bring to MD/HD commercial uses. Long-haul trucks have high vehicles miles traveled and use very large amounts of fuel. A few factors make refueling infrastructure planning for MD/HD vehicles different than planning for light-duty vehicles:

- MD/HD FCEVs are not likely to use existing refueling facilities designed for smaller, light-duty cars but require dedicated refueling stations.
- Although refueling stations for MD/HD FCEVs are likely to be different from those for light-duty FCEVs, there still exists potential of synergy across light-, medium-, and heavy-duty sectors in hydrogen production and delivery.
- Due to the nature of commercial operation, hydrogen stations for MD/HD FCEVs are more likely to have large, stable, and predictable demands.
- Long-haul freight transport requires a wide-area refueling network, but this network does not necessarily have to be dense if planned strategically. Unlike light-duty refueling, long-haul trucks typically determine their fueling locations well in advance of actual trips.

- Many MD/HD trucks operate out of depots where the fleets generally fuel each day. During the early rollout period, there may be opportunities to merge fueling stations for more than a single fleet.

In this study, we investigate the potential demand for hydrogen fuel from MD/HD vehicles in California and propose a refueling station planning framework tailored for MD/HD FCEVs. We aim to understand the following research questions:

- What are the potential population and fuel demand of MD/HD FCEVs?
- How is fuel demand from MD/HD FCEVs distributed geographically? Where are refueling facilities needed?
- What is the optimal layout for a statewide hydrogen refueling network that enables intra-state freight transportation in California?

Methodology

In this study, we break the MD/HD FCEVs market into two segments, the local market and the long-haul market, based on geographic characters of their operations. The local market consists of vehicles or fleets that operate in a local area, and travel to a fixed central location (e.g., a base yard or a central workplace) daily. This type of operation makes it feasible to provide hydrogen fuel only at or near the central locations to refuel entire FCEV fleets. Package distribution centers, bus fleet yards, and ports are examples in the local FCEV. The long-haul market consists of vehicles or fleets that travel to distant destinations and need refueling on route. A wide-area refueling network is required for this market.

A key challenge for providing hydrogen refueling for local markets is identifying clusters of such demand points and locating refueling facilities at or reasonably close to them. To estimate hydrogen demand from the local market, we

- Identify MD/HD fleets that have high potential of adopting hydrogen vehicles
- Collect geographic and operation information for such fleets
- Estimate FCEV population growth in these fleets
- Determine the vehicle miles traveled (VMT) and the fuel economy for each vehicle type
- Combine FCEV population estimate and fleet geographic information, to produce hydrogen fuel demand estimates and the spatial distribution
- Locate hydrogen refueling facilities to cover the demands
- Estimate the capacities needed at each refueling facility

For the long-haul market, it is important to provide a network of refueling stations so that long-haul vehicles can receive sufficient fuel to complete their trips. This involves strategically placing refueling facilities along California's freight transport network. We approach solutions for this market segment by:

- Identifying the most important freight transport corridors in California
- Picking candidate locations for placing hydrogen refueling facilities
- Strategically choosing candidate locations to fulfill the refueling needs, while minimizing infrastructure development needs
- Estimating the capacities needed at each refueling facility

Hydrogen Demand and Locations for Local MD/HD FCEVs

We first abstract the fuel demand from local MD/HD FCEVs to demand *points*. This is done by considering all local FCEVs as part of a fleet, and each fleet refuel at a central hub location. For each fleet, we first estimate its population growth over our analysis years, and then translate the population into fuel demand. Fleet-by-fleet FCEV population estimate is based on an exogenously defined, state-level aggregated estimate of FCEV population. Our model then adds spatial resolution to the population estimates, by distributing them to hub locations via simulating an allocation procedure where fleets already operating FCEVs and fleets spatially close to other FCEV fleets are first considered for assigning new FCEVs. After this spatial allocation, all FCEVs are kept track of their age, and become retired following to a survival curve. Every fleet's hydrogen fuel demand is then calculated from its active FCEV population, travel mileage, and vehicle fuel efficiency. With the above operations, fuel demand of local FCEVs become concentrated points, making it easy to model refueling facility placement with a p-median or a min/max cover model.

With the point demand abstraction, we formulate the refueling station optimization as a min-cover problem. We specify a threshold for coverage and minimize the total number of refueling locations needed to cover all demand points. For example, if we choose 10 minutes as a coverage threshold, then the objective would be to find the layout that minimizes total number of refueling locations, while guaranteeing every demand point is within 10-minute reach from at least one refueling location.

A few pieces of data are combined to estimate the FCEV population and their fuel demand:

Aggregated fuel demand. A higher-level, aggregated (e.g., California state total) estimate of FCEV population is taken as an input. Our model then distributes that aggregated population estimate among relevant locations throughout the state.

Fleet information. A list of fleets that are potential FCEV adopters. For each fleet we need to specify its vehicle type, fleet size, and hub location. In this study we collected information about 266 potential FCEV early adopter fleets, including package delivery fleets, bus fleets, port trucks and airport trucks. Note that although some vehicles are not administratively organized as part of any fleet, like in the case of an owner-operator truck that transports cargo in and out of a port, they are considered as one fleet for refueling facility concerns since their activities converge a central location.

Fleet VMT and vehicle fuel economy. Our model needs to know each fleet's average daily vehicle miles travelled (VMT), and each vehicle type's average fuel efficiency in miles per kilogram of hydrogen (MPkgH2).

Driving time between fleet hubs. The closeness between hubs is measured by real-world driving time in minutes. We designed our model to automatically collect such information from the Google Maps Distance Matrix API [18].

Fleet-by-fleet FCEV population is estimated by splitting an exogenously defined, aggregated state total FCEV population growth estimate to relevant fleets. The state total FCEV growth is expressed in estimated new FCEV population for each vehicle type for each model year. Figure 3 shows a sample scenario that targets for 40,000 local FCEVs by 2030.

The state total growth is seen as a "supply" of FCEVs, and all fleets around the state "compete" for such supply. We implement a scoring mechanism to facilitate allocating each model year's new FCEVs to fleets. Priority is given to fleets that already operate FCEVs and fleets that are geospatially close to existing FCEV fleets. Additionally, to break the situation where no one takes the first step, we hand-picked "seed" years for some fleets, and give them extra priority when allocating.

A more detailed description of the simulated allocation procedures is listed as follows:

- In each year, every fleet is given a score based on a number of factors (discussed below). Then the model iterates through all fleets from high-score to low-score and decide FCEV allocations.
- Higher-score fleets get allocated new FCEVs as many as they need, or as there are available in the statewide quota left, whichever is smaller. Lower-score fleets are considered after higher score fleets.
- A fleet's total vehicle population is limited by its fleet size cap. No fleet will be allocated more FCEVs than what is sufficient to reach its fleet size cap.

In each year, a fleet's score is calculated in the following way:

- If it is a seed year of a fleet, it receives 10 points.
- If a fleet already has FCEVs, it receives 8 points.
- If a fleet shares a hub location with another FCEV fleet, it receives 5 points.
- If a fleet is close to one or more other FCEV fleets, it receives a score based on closeness to the nearest FCEV fleet.
- The highest score from items 1-4 becomes a fleet's final score, which is used for ranking fleets and deciding allocation of FCEVs.

The score points show above are arbitrarily selected and can be easily customized to weigh in different priority concerns.

After new FCEVs are allocated, our model keeps track of each fleet's vehicle stock inventory. Old vehicles are gradually reduced per a survival curve to account for loss, depreciation, or retirement. The survival curve describes at each age, what proportion of the original population survives. Figure 1 shows the survival curve we used in our model. It is obtained from the VISION planning model by California Air Resources Board [19]. With each year's new FCEV population and inventory of old FCEVs, we are able to calculate every fleet's vehicle population in every year, for every age.

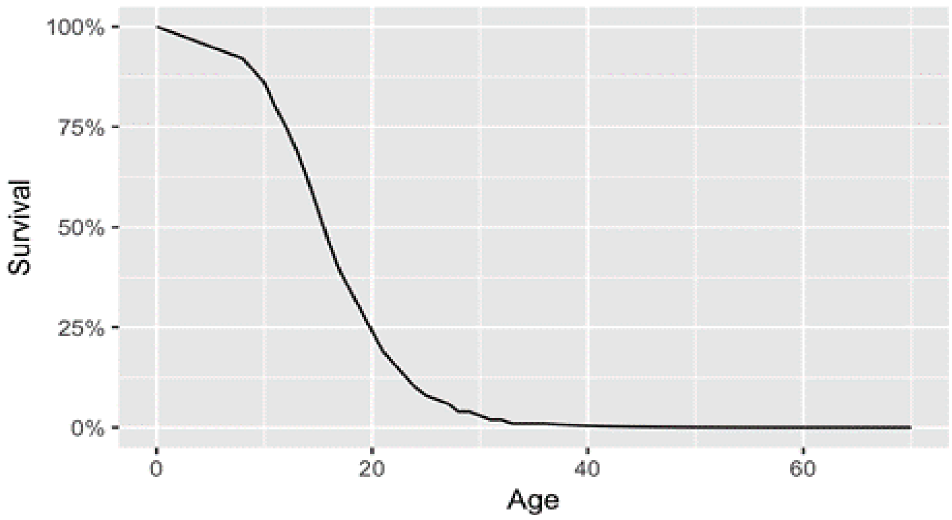


Figure 1. Vehicle survival curve

Location-by-location fuel demand is calculated by combining the fuel demand from all vehicles refueling at that location. Every fleet is associated with a daily VMT in the fleet specification, and every type of vehicles has a fuel efficiency. Combining VMT, fuel efficiency, fleet size, and fleets sharing a hub location will yield the daily hydrogen demand (in daily kgH2) at each location.

After hydrogen demand from all hub locations are calculated, we run the location optimization model to find a subset of these hub locations to place refueling stations. For the local FCEVs, we use the Network Analyst feature of ArcGIS [20] to find a minimum set of refueling station locations that ensures all hydrogen demand points can access a refueling station within 10 minutes. The road network used for measuring driving time is based on 2015 road GIS data from US Census Bureau’s Topologically Integrated Geographic Encoding and Referencing (TIGER) database [21].

Refueling Network for Long-Haul MD/HD FCEVs

The refueling demand from long-haul FCEVs are abstracted as *trips* rather than points. We first model California’s truck route system as a network graph, consisting of nodes and arcs. Trips are then defined based on this network graph. Each trip is characterized by an *origin-destination pair* (OD pair), a *path*, and a *volume*. A trip’s OD is the pair of nodes that trip starts and ends at. The path a trip takes is described by the sequence of nodes it traverses through. The volume of a trip is the number of repetitive trips taken on a specific path during a period of time, for example, daily trip counts.

We then optimize the refueling locations on the truck route network graph, by minimizing the total number of refueling stations while satisfying refueling need of all trips. This optimization problem can be formulated as an integer programming (IP) problem, and we use the Gurobi Optimizer software [22] to solve it. When the optimal refueling station layout is obtained from the previous step, refueling capacity needed at each station can be calculated by accumulating the trips visiting that station.

We construct a network graph model to represent the key components in California's truck route network. It is formatted as nodes and arcs. Nodes in this graph include important cities, loading and unloading points like ports and airports, major highway intersections, and existing truck service locations (e.g., truck stops, parking areas). All nodes are considered as candidate sites for new hydrogen refueling stations. Each node is associated with a physical location represented by latitude and longitude coordinates.

Arcs in the network graph are roadways connecting the nodes, and each arc is associated with a driving distance, which is obtained from Google Maps Distance Matrix API [18]. Trip paths are modeled as sequences of nodes and arcs. The exact paths taken by a trip can be customized, but by default we use the shortest path between OD, found with the NetworkX [23] implementation of Dijkstra's algorithm [24].

We formulate the refueling location optimization problem as an integer programming problem. The formulation follows a similar framework of the Flow Refueling Location Model by Kuby et. al [12, 14, 15], but with minor changes. The objective is to minimize total number of stations, and the FCEVs' range constraints must be met.

The mathematical formulation of this IP problem is expressed as follows:

Define:

N = total number of nodes in the network graph. Since all nodes are candidate sites for refueling stations, N is also the total number of candidate sites.

$x_i \in \{0,1\}$ are decision variables. $i \in \{1,2,3,\ldots N\}$ refers to a node. $x_i = 1$ when node I is chosen as a refueling station location, and $x_i = 0$ when otherwise.

T = set of all paths

Qt = set of all nodes on path t

R = range of FCEVs (maximum distance an FCEV can travel after a full refuel)

The objective is to minimize the sum of x_i over all nodes subject to $x_i = 1$ for all t belonging to T and all I belonging to Qt.

This optimization problem has a binary integer programming formation, in which the decision variables are simply whether or not to choose a node as a refueling station. Guarantee of sufficient fuel for all trips is provided by the constraints in equation (2), which says that for each node, *i*, on each path *t*, there exist at least one refueling facility among nodes *j* where a vehicle can refuel and reach node *i*. When we guarantee that each node on each trip can be reached, we guarantee all trips can be completed.

There are many linear constraint inequalities, and the construction of sets $F_{t,6,F}$ is in practice a non-trivial work, thus it is further explained here. Recall that each trip is represented by a sequence of nodes. For each node *i* on path *t*, given vehicle range *R*, there are only a certain set of nodes where a vehicle can refuel and reach node *i* without other refuels: the nodes that are upstream of node *i* on trip *t*, and no farther away than *R*. We call this set of nodes $F_{t,6,F}$.

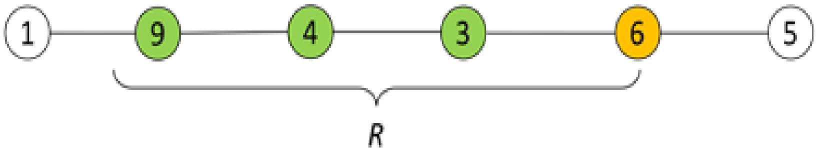


Figure 2. Sample path t, and nodes that can provide fuel for reaching node 6 on this path

Figure 2 illustrates an example path, *t*, consisting of 6 nodes with node IDs 1, 9, 4, 3, 6, 5. Take node 6, for instance, given the range, *R*, as illustrated in Figure 2. If a vehicle refuels (to full tank) either at node 9, 4, or 3, it can reach node 6 without running out of fuel. If the vehicle refuels at node 1, however, it won't be able to reach node 6 without another refueling because the driving distance is beyond its maximum range. Therefore, for this particular node (node ID=6) on this particular trip (trip ID=*t*), $F_{t,6,F}$ = 9, 4, 3. In order for any vehicle that has range *R* to be able to reach node 6 on trip *t*, there must be at least one refueling station among nodes 9, 4, or 3. An $F_{t,6,F}$ set is constructed for each path's each node, and a linear constraint in a form similar to the above constraint is added to the mathematical programming problem.

Data

To investigate local FCEV fleets and hubs, we collected real-world location data of potential FCEV fleet hubs in California from various public sources. Our FCEV hubs dataset contains 266 hub locations, falling into 5 categories: airports (12 locations), bus yards (42 locations), industrial parks (69 locations), package delivery centers (134 locations), and ports (9 locations).

Due to lack of real-world fleet information, in this study we assume each hub location has one and only one fleet. We make further assumptions about each fleets' vehicle types, seed years, and fleet size caps, based on the location type and industrial experience. (Table 1)

Projection about the growth of MD/HD FCEVs is an exogenous input to our model. As a baseline scenario, we assume a FCEV growth pattern that targets 40,000 locally operated FCEVs by 2030, based on the 100,000 zero emission freight vehicle by 2030 goal proposed in the California Sustainable Freight Action Plan [1]. Further, we assume 4 vehicles types and their respective 2030 population targets within the 40,000 local FCEVs:

1. Medium-duty package delivery vehicles: 10,000
2. Heavy-duty port drayage trucks: 15,000
3. Heavy-duty transit buses: 5,000
4. Heavy-duty other drayage trucks: 10,000

In addition to the 2030 targets, we assume a linearly growing pattern in the yearly new FCEV population targets over our analysis period (2018 and 2030). Figure 3 illustrates this "linear-growth to 40K" scenario.

All local FCEVs are assumed to travel 150 miles per day. This is a highly simplified assumption, but it matches with the survey findings about medium-duty trucks like [27]. The FCEV fuel efficiency data, as summarized in Table 2, is obtained from simulation results from Burke et. al [28].

Table 1. Example table

Fleet hub location type	Vehicle type	Fleet size cap
Port	HD port drayage	14000
Airport	HD other drayage	100
Package delivery center	MD package delivery	350
Bus yard	HD transit bus	varies by fleet

Table 2. FCEV fuel efficiency assumptions

FCEV type	Fuel efficiency (MPkgH2)
Transit buses	13.9
MD package delivery trucks	20
HD drayage trucks	15

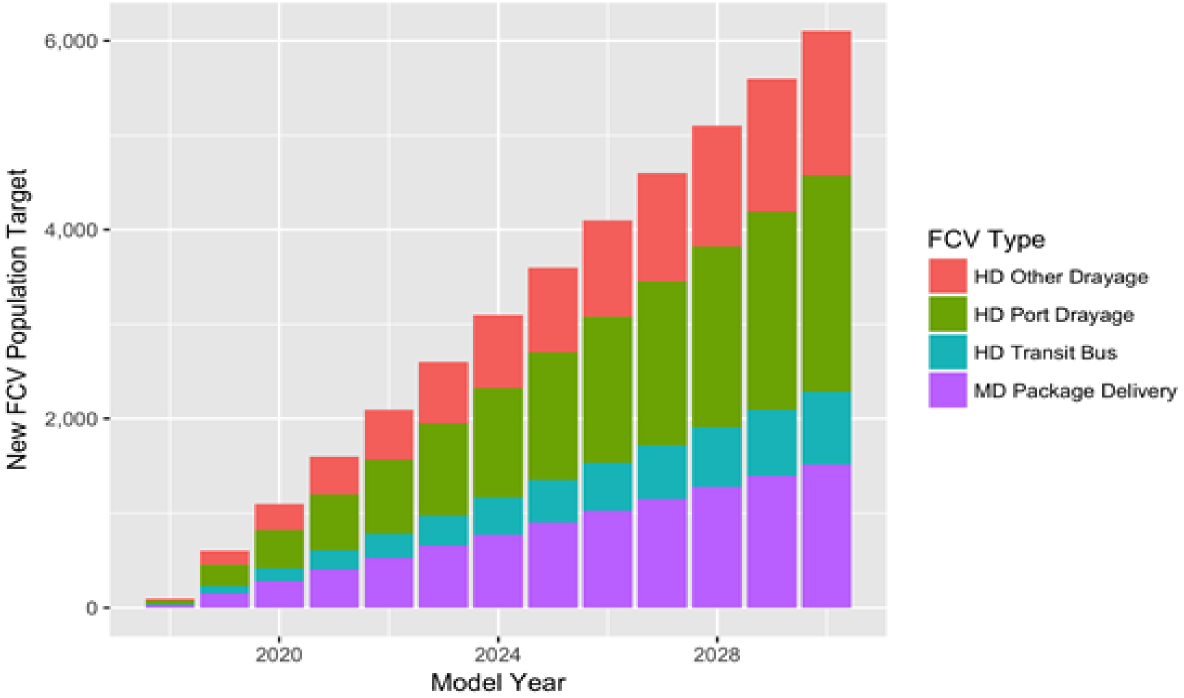


Figure 3. Statewide FCEV growth scenario to meet a target of 40,000 local FCEVs by 2030

To investigate long haul trucking refueling candidate sites, we use the method discussed above to build a network graph model based on California's truck route network. The nodes, i.e., candidate refueling facility sites, are selected based on three criteria:

1. Intersections of major truck routes.
2. Inter-modal transfer points, such as ports and airports.
3. Existing truck service facilities along major highways (e.g., truck stops).

Data sources for these locations include Caltrans GIS Library [28], Caltrans Office of Freight Planning [29], and US Department of Transportation Federal Highway Administration [30]. A total of 75 nodes and 86 arcs are used in the California truck network graph (illustrated in Figure 4).

Figure 4. California truck network graph

Among all 75 nodes in our network graph, only 20 are considered as origins and destinations (ODs) of freight trips. The “OD nodes” are ones located in metropolitan areas, and the non-OD nodes are ones far away from dense population thus not likely to be a major freight origin or destination. Between every OD, the shortest path within our network graph is used as the trip path.

Traffic volumes (trip counts) between ODs are adapted from heavy-duty commercial vehicle (HCV) travel demand forecast from Caltrans’ California Statewide Travel Demand Model (CSTDM) [31]. CSTDM provides county-to-county daily trip count forecast for 2040. We select only the HCV trips, and map the county-to-county trips to node-to-node trips. Among all 58 counties of California, only those that host at least one OD node are considered. There end up being 15 such counties, and trips among them account for 62.4% of all HCV trips modeled in CSTDM. Trip counts on each county-county pair is then evenly split among all node-node pairs starting/ending in that county-county pair. In total, we identified 380 OD pairs. 2,308,760 daily HCV trips are spread across these ODs.

Results

Following the local FCEV growth targets and the spatial distribution method described above we can estimate the FCEV population in each local fleet for each analysis year. Figure 5 shows an aggregation of the FCEV population over the 2018-2030 period by vehicle type. All four types of vehicles grow close to their respective population targets but fall short by a small amount due to fleet size limitations and depreciation of aged vehicles.

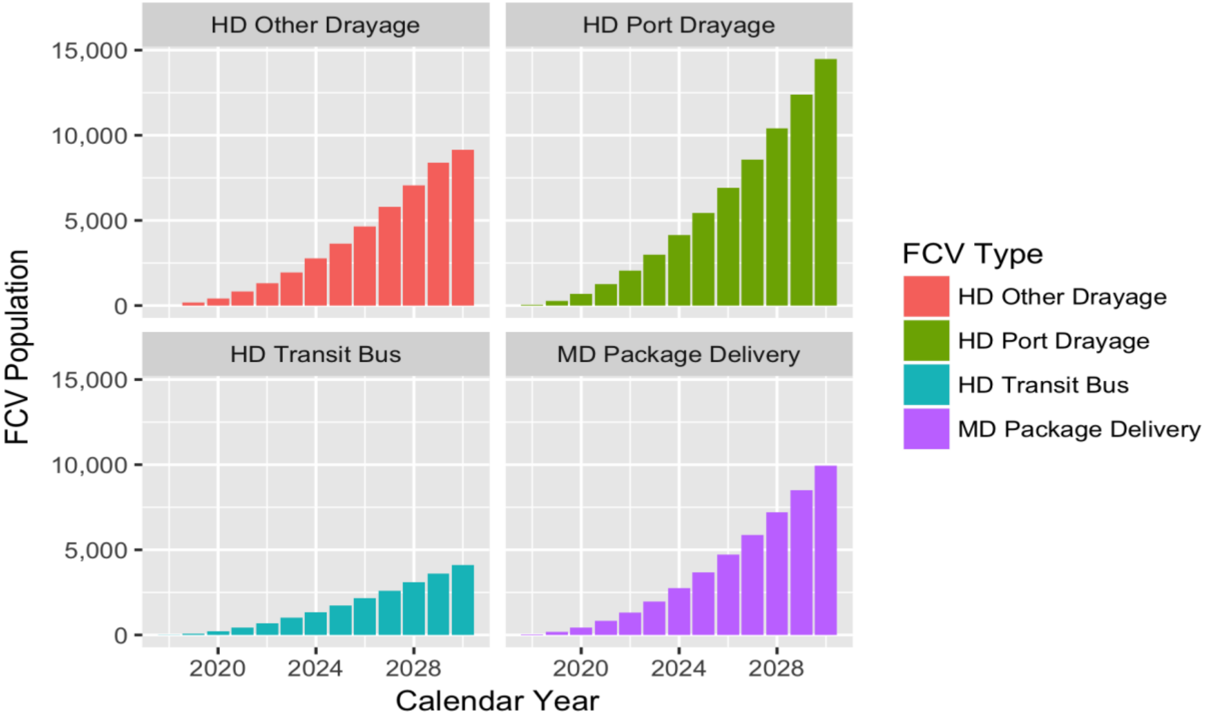


Figure 5. Local FCEV stock by vehicle type, 2018-2030

The fuel demand from local FCEVs is summarized in Figure 6. Hydrogen demand across the state grows from less than 1,000 kgH2/day in 2018 to over 350,000 kgH2/day in 2030. Figure 7 shows the spatial distribution of such demand in 2030.

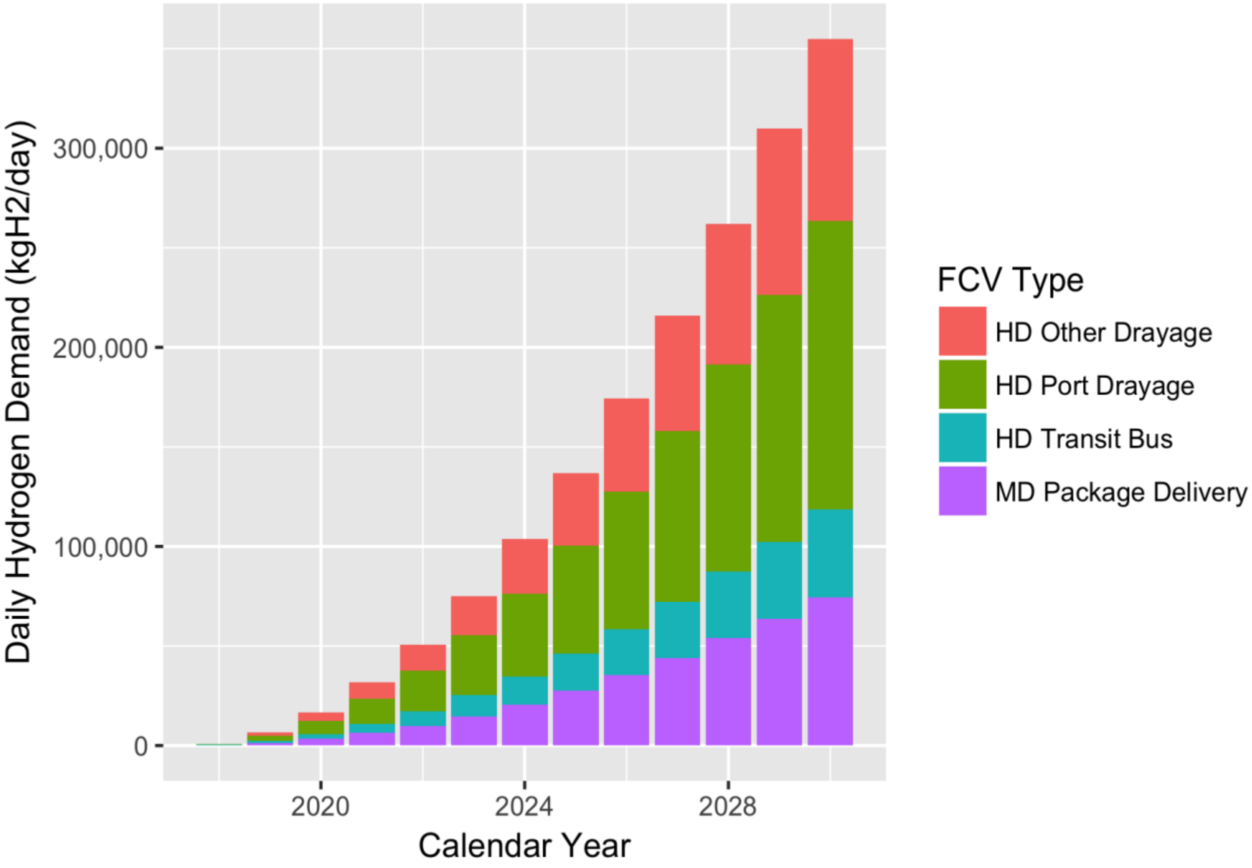


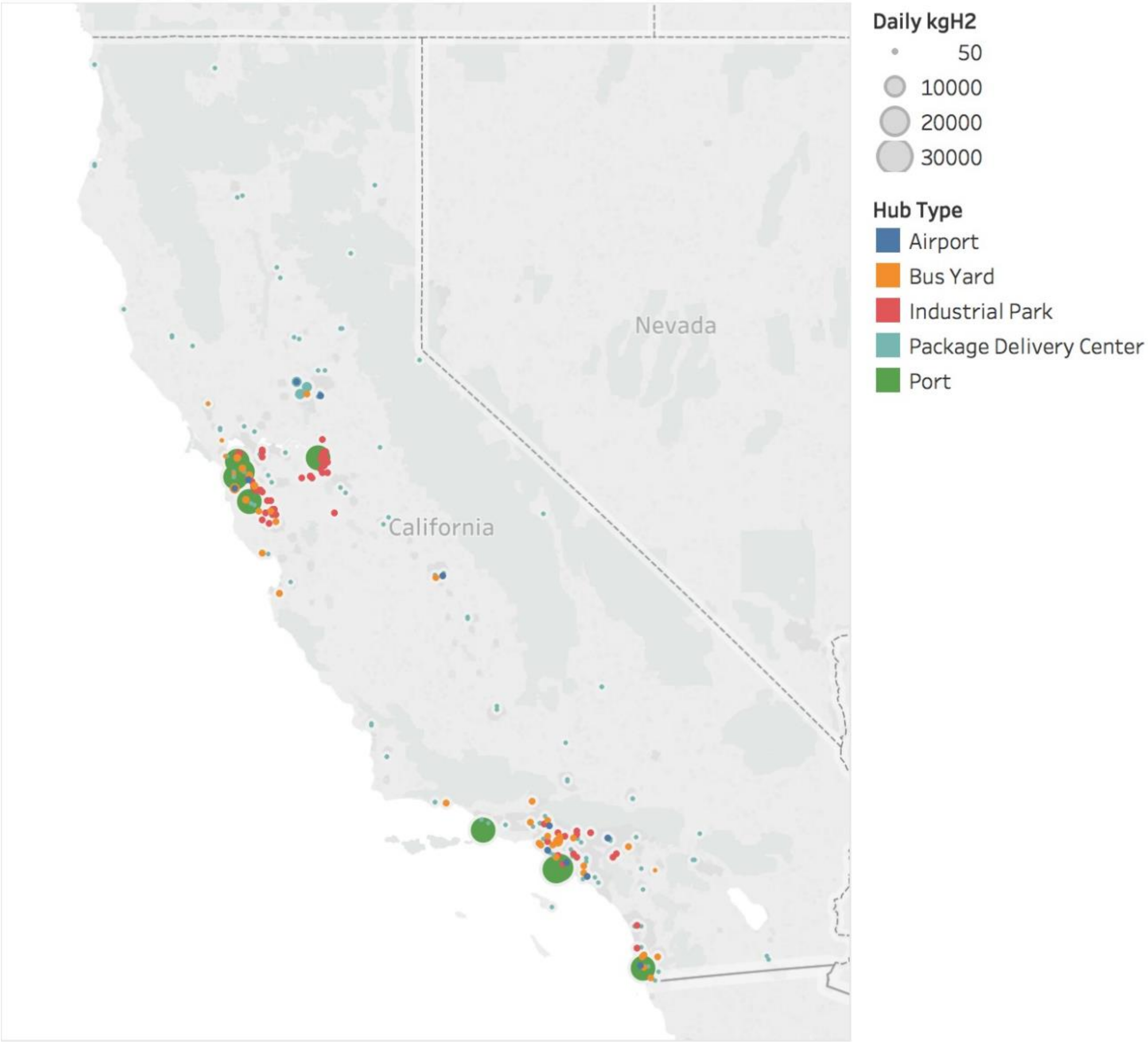
Figure 6. Local FCEV daily fuel demand, 2018-2030

Geographical concentration of local FCEV hydrogen demand is largely driven by the locations of ports, as well as clustered industrial parks and bus fleets. Ports of Los Angeles, Long Beach, San Francisco, Stockton, and San Diego are the biggest demand centers. Additional demand centers appear in major metropolitan and/or industrial areas, like Los Angeles, South and East San Francisco Bay, Stockton, and Sacramento.

Figure 8 shows a refueling station layout that provides 10-minute coverage for all local FCEVs fleets. In total, our location optimization model finds 131 refueling station sites to serve the local FCEVs.

Figure 9 shows a histogram daily hydrogen demand at these local FCEV refueling stations, which can be a rough approximation of station sizes, although actual station sizing may need extra considerations like contingency capacity. The station sizes vary from over 500 kgH2 per day to nearly 50,000 kgH2 per day. Noticeably, even the smallest station (630 kgH2/day) needs a hydrogen throughput higher than any light-duty vehicle hydrogen stations found today (usually 100-350 kgH2/day capacity). Station with sizes between 1,000 and 5,000 kgH2/day are the most common in our 2030 scenario. Extremely large stations over 20,000 kgH2/day often appear near ports, which is consistent with our aggressive targets about drayage truck population. Overall, the large hydrogen demand at these local MD/HD FCEV refueling stations pose a great challenge on station design and hydrogen dispensing technologies. In the meantime, they also offer an opportunity of reduced hydrogen cost due to scale of economy. Mass-transport of hydrogen, for example, with liquid hydrogen tubes or pipelines, may become viable options when such large demands exist.

Year 2030



Map based on Lon and Lat. Color shows details about Hub.Type. Size shows details about Daily.kgH2. The view is filtered on Daily.kgH2, which includes values greater than or equal to 50.

Figure 7. Local FCEV fuel demand map, 2030

Figure 10 demonstrates to what extend do FCEV fleets share refueling locations. Among all 131 refueling locations, 71 (accounting for 54% of all locations) are designated to a single fleet hub, and the remainder of refueling stations are shared by fleets from more than one hub. In the most extreme case, the Triangle Industrial Park station in Stockton serves 13 hubs, including many nearby industrial parks and the Port of Stockton. Although many stations are utilized only by the home fleets, there still exist significant opportunities of synergy among FCEV fleets that are geographically close by.

We propose a hydrogen refueling network for long-haul fuel cell trucks based on our optimization model described above. This network consists of 13 stations spread across the state (Figure 11).

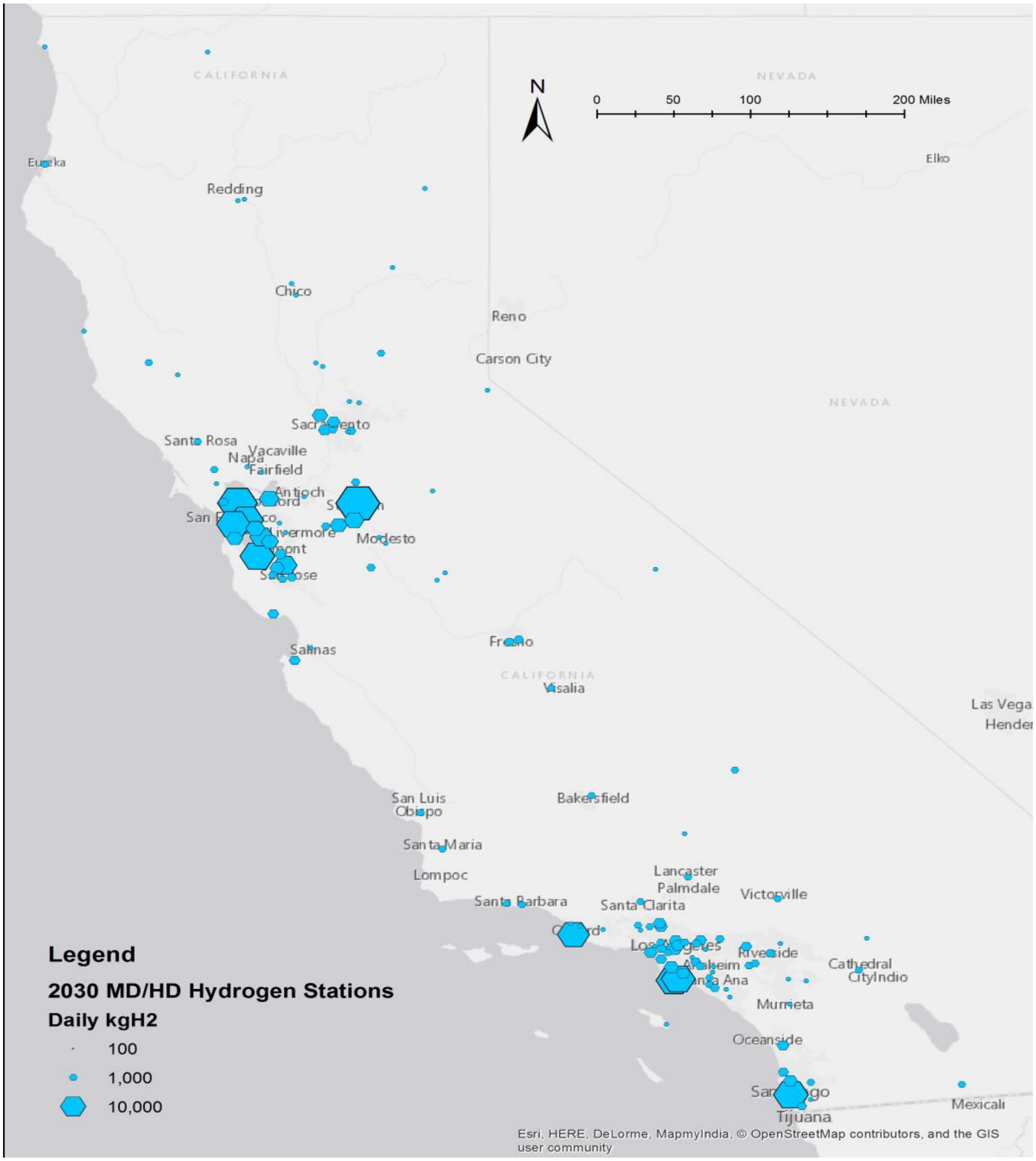


Figure 8. Hydrogen refueling stations serving the local FCEVs in 2030

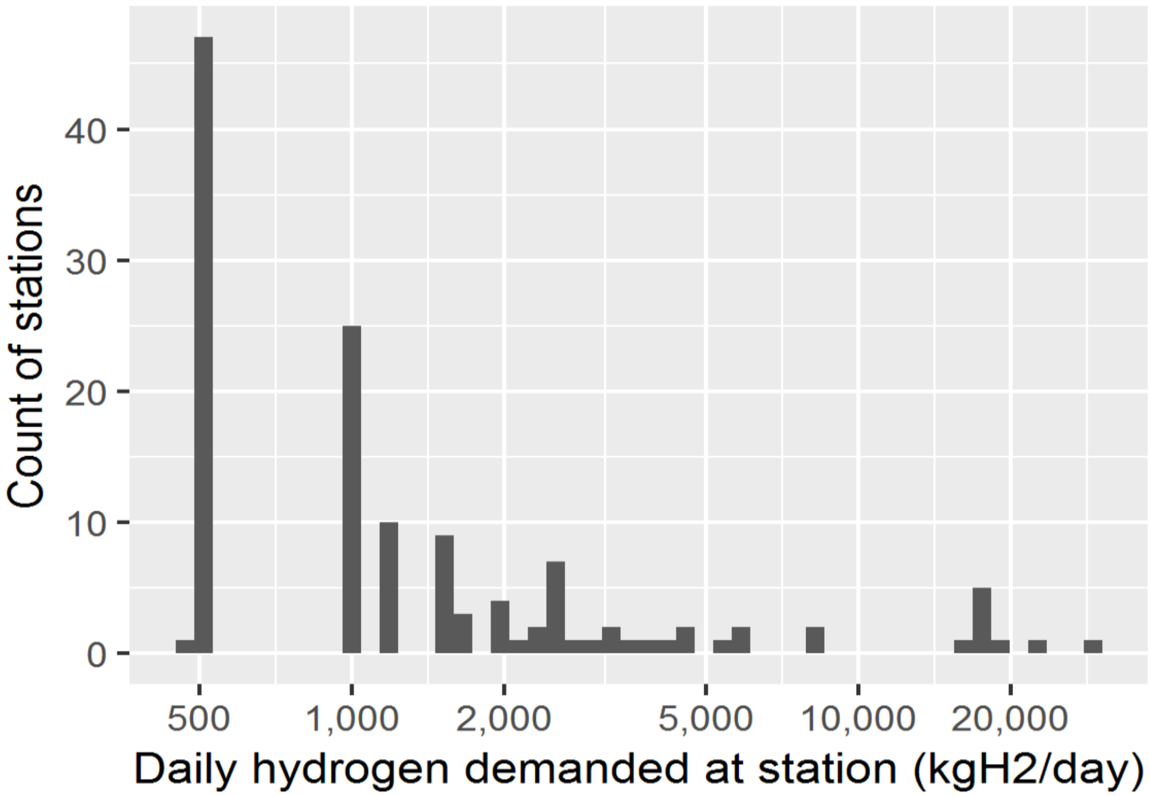


Figure 9. Histogram of daily hydrogen demand at the stations serving local FCEVs

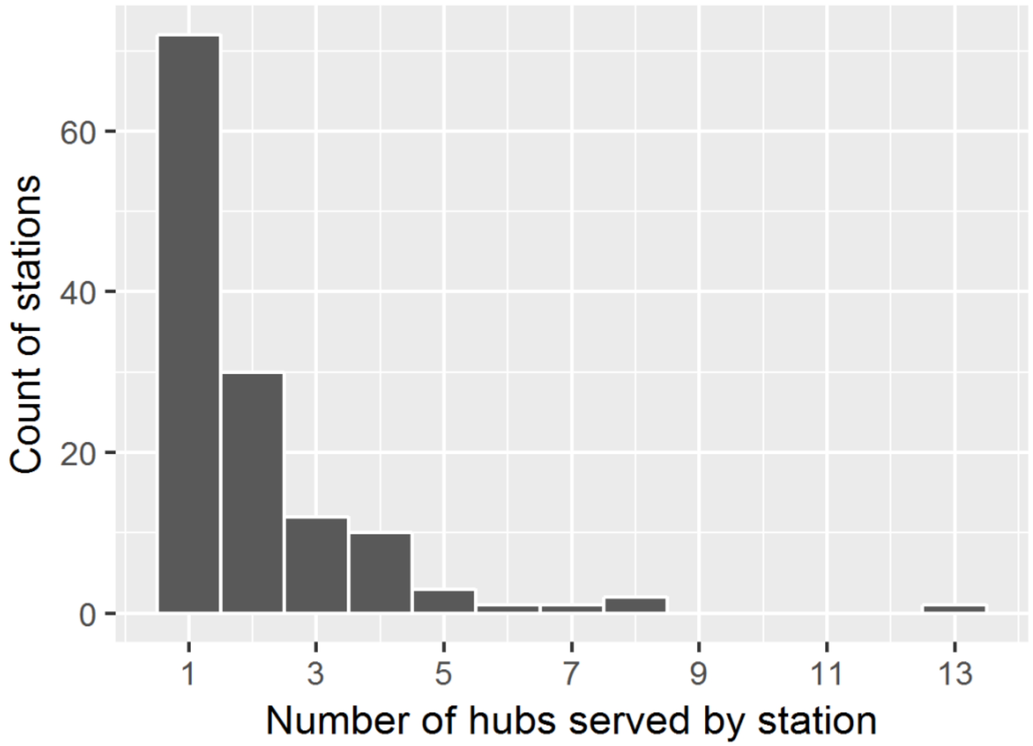


Figure 10. Histogram of number of fleet hubs served by the stations serving local fleets

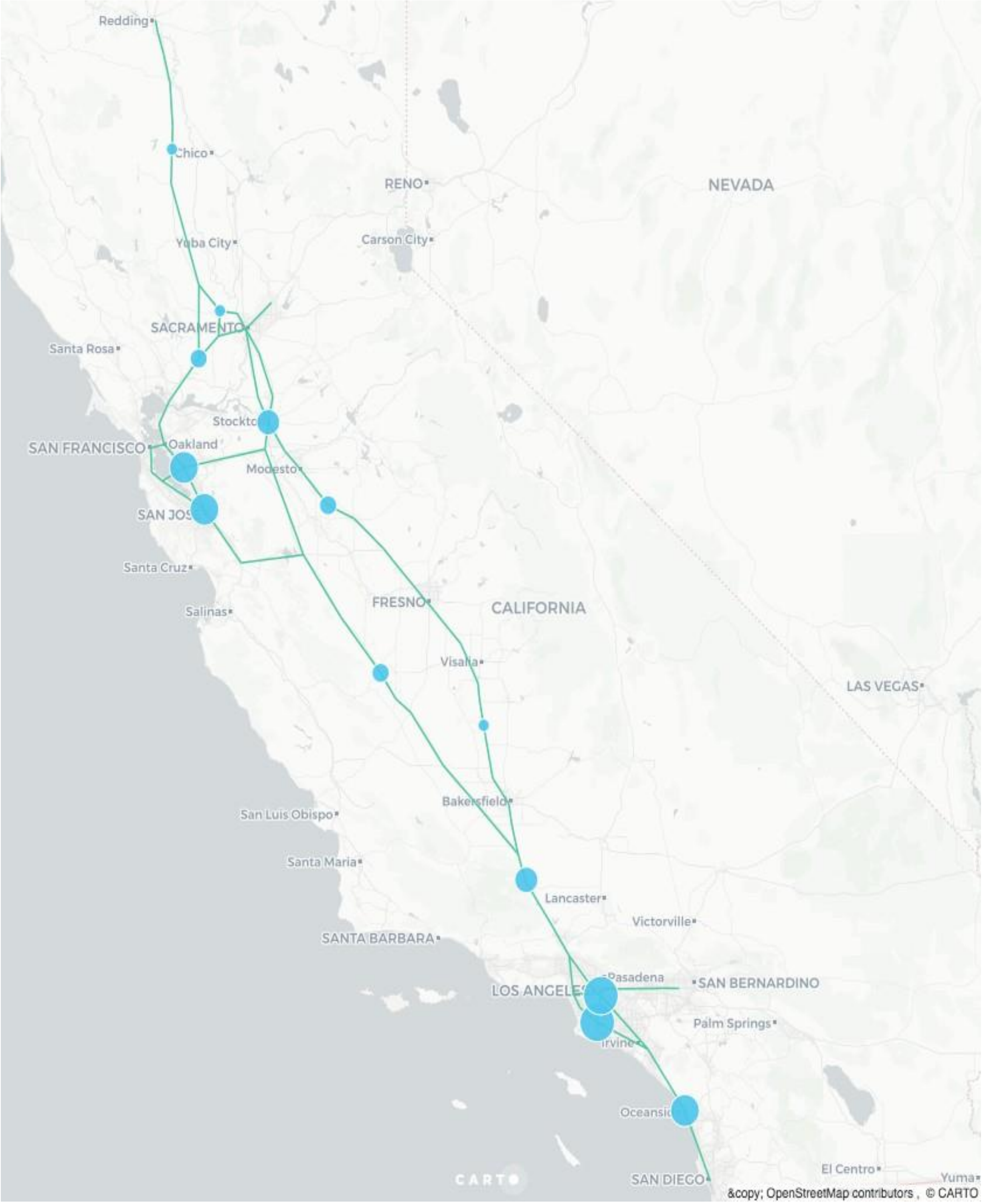


Figure 11. California statewide HRS network for long-haul FCEVs

Discussion

From this study, we have observed that the demand of hydrogen fuel from MD/HD FCEVs is heavily centered in California's two largest metropolitan areas, Los Angeles and San Francisco Bay area. Stockton and Sacramento are two additional regions of high demand. These demand centers are largely driven by locations of ports and major freight corridors. Industrial parks and bus fleet hubs are also important generators of hydrogen demand.

Although local and long-haul FCEVs have distinctive travel patterns, their preferred refueling locations overlap by a significant portion, and thus offers potentials for synergy. Los Angeles, East and South San Francisco Bay Area, and Stockton are three key areas for such synergy. These areas have both concentrated local demand and on route refueling demand because of their locations. Given that local FCEVs may penetrate the market before long-haul FCEVs, a potential form of synergy could be to prepare HRS sites near major highways, and initially serve local FCEV fleets, before long-haul FCEVs gain market momentum. While fleets generally fuel in their own depot, initial hydrogen station rollout could include shared stations. Another form of synergy could be to share hydrogen production and delivery infrastructure rather than refueling facilities. With large demand in a relatively concentrated area, liquid hydrogen/pipeline delivery or even designated hydrogen plants can eventually become viable.

As an early effort on the topic the MD/HD FCEVs, our study has some noticeable limitations. First, we lack good data on many key inputs, such as truck fleet information, fuel cell truck performance, and real-world truck traffic routing. Additionally, the simplifications we make in this model remain to be improved.

For example, the simplified truck route network we used for long-haul trips completely ignores the coastal highway and adjacent cities, like the Monterey region and Santa Barbra region. With further FCEV population growth, the less traveled regions will need to be addressed as well. Lastly, our model also ignores many practical considerations in real-world infrastructure development. For example, large scale hydrogen station can impose land use challenges which may prevent them from being placed at certain locations, and such aspects are not addressed in our model.

Conclusions

Some insights from this study on the topic of MD/HD hydrogen FCEV refueling infrastructure are summarized below:

- ZEVs must grow very aggressively to meet the state's freight ZEV targets. Around 2030, tens of thousands of ZEVs must come into the market every year. While battery electric trucks seem to have a head start on commercialization, FCEVs have advantages that could make them preferred in certain markets such as long-haul trucking.
- Hundreds of metric tons of daily hydrogen supply will be needed by 2030 to support the local hydrogen fleets projected in this study, and the refueling stations vary by size, from 1,000 kg per day to nearly 50,000 kg per day.
- For the long-haul truck operations, we can build a statewide "backbone" hydrogen refueling network with about 13 strategically located refueling stations. This backbone does not cover the entire state. Coastal highways and cities would require hydrogen infrastructure in addition to the network described here.
- There exists potential of synergy between the refueling infrastructure of local and long-haul FCEVs. Los Angeles, East and South San Francisco Bay, and Stockton are key areas of such synergy. These synergies may be crucial to the initial rollout of MD/HD truck hydrogen stations
- Many hydrogen stations are shared by fleets from more than one hub. Among all 131 refueling locations, 60 or 46%, are shared. The Triangle Industrial Park station in Stockton serves 13 hubs.

References

1. E. G. B. Jr., The California sustainable freight action plan 2016, July 2016. http://www.casustainablefreight.org/theplan.html
2. M. Ehsani, Y. Gao, A. Emadi, Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design, CRC press, 2017.
3. C. Thomas, Fuel Cell and Battery Electric Vehicles Compared, International Journal of Hydrogen Energy 34 (15) (2009) 6005–6020.
4. L. Eudy, M. B. Post, Fuel Cell Buses in US Transit Fleets: Current status 2017, Tech. rep., National Renewable Energy Lab (NREL), Golden, CO United States 2017.
5. I. Ahmed, Fedex Express Hydrogen Fuel Cell Extended-range Battery Electric Vehicles June 2017.
6. J. O'Dell, UPS launching world's first fuel cell electric class 6 delivery truck [online] May 2017.
7. J. Voelcker, Toyota "Project Portal" hydrogen fuel cell heavy-duty semi tractor as proof of concept. Accessed online 2/13/2020. https://www.greencarreports.com/news/1109999_toyota-project-portal-hydrogen-fuel-cell-heavy-duty-semi-tractor
8. J. O'Dell, Nikola to start fuel cell truck field tests in late 2018; Names fuel cell suppliers, accessed online 2/13/2020. https://www.trucks.com/2017/11/09/nikola-fuel-cell-truck-field-test-2018/#:~:text=Nikola%20to%20Start%20Fuel%20Cell%20Truck%20Field%20Tests,2018%3B%20Names%20Fuel%20Cell%20Suppliers&text=Nikola%20Motor%20Co.,expected%20to%20start%20in%202021.
9. M. Nicholas, S. Handy, D. Sperling, Using geographic information systems to evaluate siting and networks of hydrogen stations, Transportation Research Record: Journal of the Transportation Research Board (1880) (2004) 126–134.
10. Z. Lin, J. Ogden, Y. Fan, C.-W. Chen, The fuel-travel-back approach to hydrogen station siting, International journal of hydrogen energy 33 (12), 2008, 3096–3101.
11. S. D. Stephens-Romero, T. M. Brown, J. E. Kang, W. W. Recker, G. S. Samuelsen, Systematic planning to optimize investments in hydrogen infrastructure deployment, international journal of hydrogen energy 35 (10), 2010, 4652–4667.
12. M. Kuby, S. Lim, The flow-refueling location problem for alternative-fuel vehicles, Socio-Economic Planning Sciences 39 (2) (2005) 125–145.

13. M. Kuby, L. Lines, R. Schultz, Z. Xie, J.-G. Kim, S. Lim, Optimization of hydrogen stations in Florida using the flow-refueling location model, International Journal of Hydrogen Energy 34 (15) (2009) 6045–6064. doi:http://dx.doi.org/10. 1016/j.ijhydene.2009.05.050. http://www.sciencedirect.com/science/article/pii/S0360319909007563

14. I. Capar, M. Kuby, V. J. Leon, Y.-J. Tsai, An arc cover–path-cover formulation and strategic analysis of alternative-fuel station locations, European Journal of Operational Research 227 (1) (2013) 142–151.

15. S. Hong, M. Kuby, A threshold covering flow-based location model to build a critical mass of alternative-fuel stations, Journal of Transport Geography 56 (2016) 128–137.

16. ARB, Hydrogen fueling infrastructure assessments (2017). https://ww2.arb.ca.gov/sites/default/files/2020-03/chit_release_2017_webinar_presentation_ac.pdf

17. B. Bush, M. Melaina, M. Penev, W. Daniel, Sera scenarios of early market fuel cell electric vehicle introductions: Modeling framework, regional markets, and station clustering, Tech. rep., National Renewable Energy Lab. (NREL), Golden, CO (United States) (2013).

18. Google, Google Maps Distance Matrix API.

19. California Air Resources Board, Vision scenario planning. https://ww2.arb.ca.gov/resources/documents/vision-scenario-planning

20. ESRI, ArcGIS 10.4 for Desktop, (2016).

21. U.S. Census Bureau, Tiger/line shapefiles and Tiger/line files 2015. https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2015.html

22. I. Gurobi Optimization, Gurobi optimizer reference manual, 2016. http://www.gurobi.com

23. A. A. Hagberg, D. A. Schult, P. J. Swart, Exploring Network Structure, Dynamics, and Function Using Networks, in G. Varoquaux, T. Vaught, J. Millman, (Eds.), Procee3dings of the 7th Python in Science Conference, Pasadena, CA, USA, 2008, pp. 11-15.

24. E. W. Dijkstra, A note on two problems in connexion with graphs, Numerische Mathematik 1 (1) (1959) 269–271. doi: 10.1007/bf01386390. https://doi.org/10.1007/BF01386390

25. California Air Resources Board, Public workshops on the development of the advanced clean transit regulation, May 2015.

26. California Air Resources Board, Fleet rule for transit agencies reported compliance for 2015, August 2015.

27. C. Mahrle, M. Hartl, G. Wachtmeister, M. Fries, S. M. M. Lienkamp, W. Wilden, F. Frenkler, B. G¨anßbauer, W. Bick, Bayerische kooperation fur transporteffizienz truck 2030, Report, Bayerische Forschungsstiftung, 2016. https://mediatum.ub.tum.de/1350441

28. A. Burke and H. Zhao, Fuel Economy Analysis of Medium/Heavy-Duty Trucks: 2015 – 2050, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-49. https://itspubs.ucdavis.edu/publication_detail.php?id=2863
29. Caltrans, 2011 truck network, 2011. http://www.dot.ca.gov/hq/tsip/gis/datalibrary/Metadata/Trknet.html
30. Caltrans, Freight planning fact sheets, 2014 http://www.dot.ca.gov/hq/tpp/offices/ogm/fact_sheets_index.html
31. USDOT, Truck parking FHWA freight management and operations, 2013. http://ops.fhwa.dot.gov/freight/infrastucture/truck_parking/index.htm
32. Caltrans, California statewide travel demand model, Technical rep., California Department of Transportation, 2014 https://scag.ca.gov/post/california-statewide-travel-demand-model-january-22-2014