Hydrogen Demand and Refueling Infrastructure Planning for Medium- and Heavy-Duty Fuel Cell Vehicles in California

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Institute of Transportation Studies, UC Davis

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STEPS Fall 2017 Symposium

UC DAVIS
SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS
An Institute of Transportation Studies Program

We Built a Model

- To understand infrastructure planning questions for MD/HD FCVs
- Local FCVs
  - Population
  - Location
  - H2 Demand
  - Refueling Station Location & Size
- Long-haul FCVs
  - Truck Route Network
  - Refueling Station Location & Size

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Two Markets

Local
- Package delivery trucks
- Drayage trucks
- Transit buses

Photo credit to: UPS


Photo credit to: AC Transit


Photo credit to: Toyota

Long-haul
- HD tractors

Photo credit to: Nikola Motor

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Local FCVs

Fleets

- Population
- Hub (location)
- H2 Demand

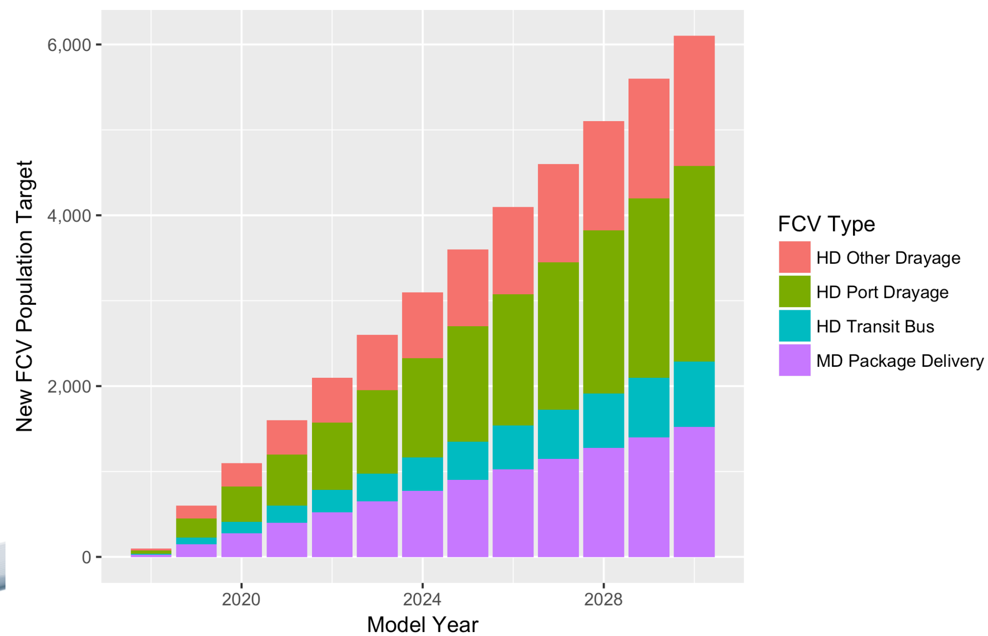
Refueling Stations

- Location
- Size

Local FCVs: How Many & Where

FCV population target

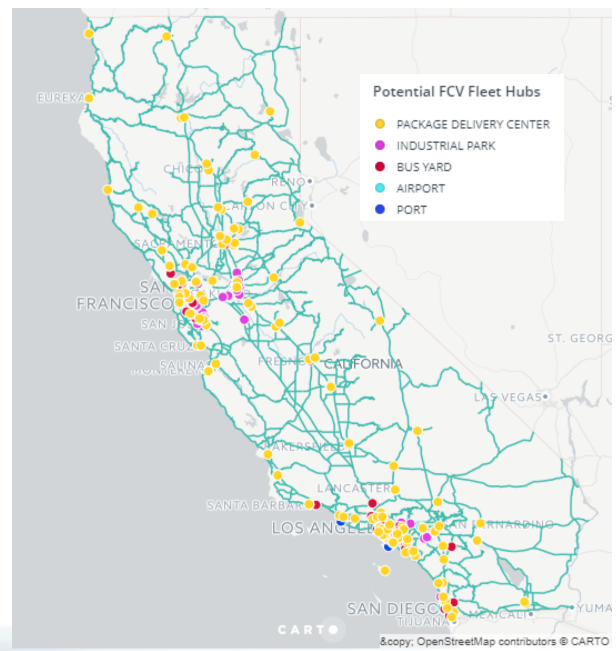
- California targets* 100,000 zero-emission freight vehicles by 2030
- We assume 40K local FCVs by 2030



*: Brown, E. G. (2016). California Sustainable Freight Action Plan.

FCV fleets & hubs

- Ports, airports, package delivery centers, bus yards, industrial parks (266 hubs)



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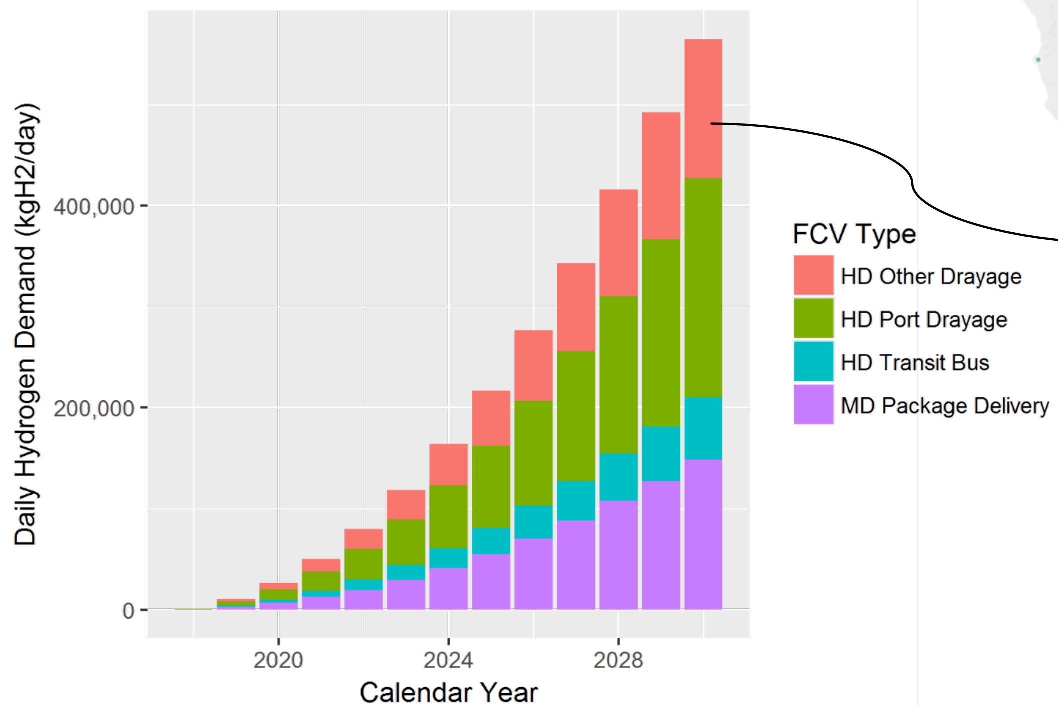
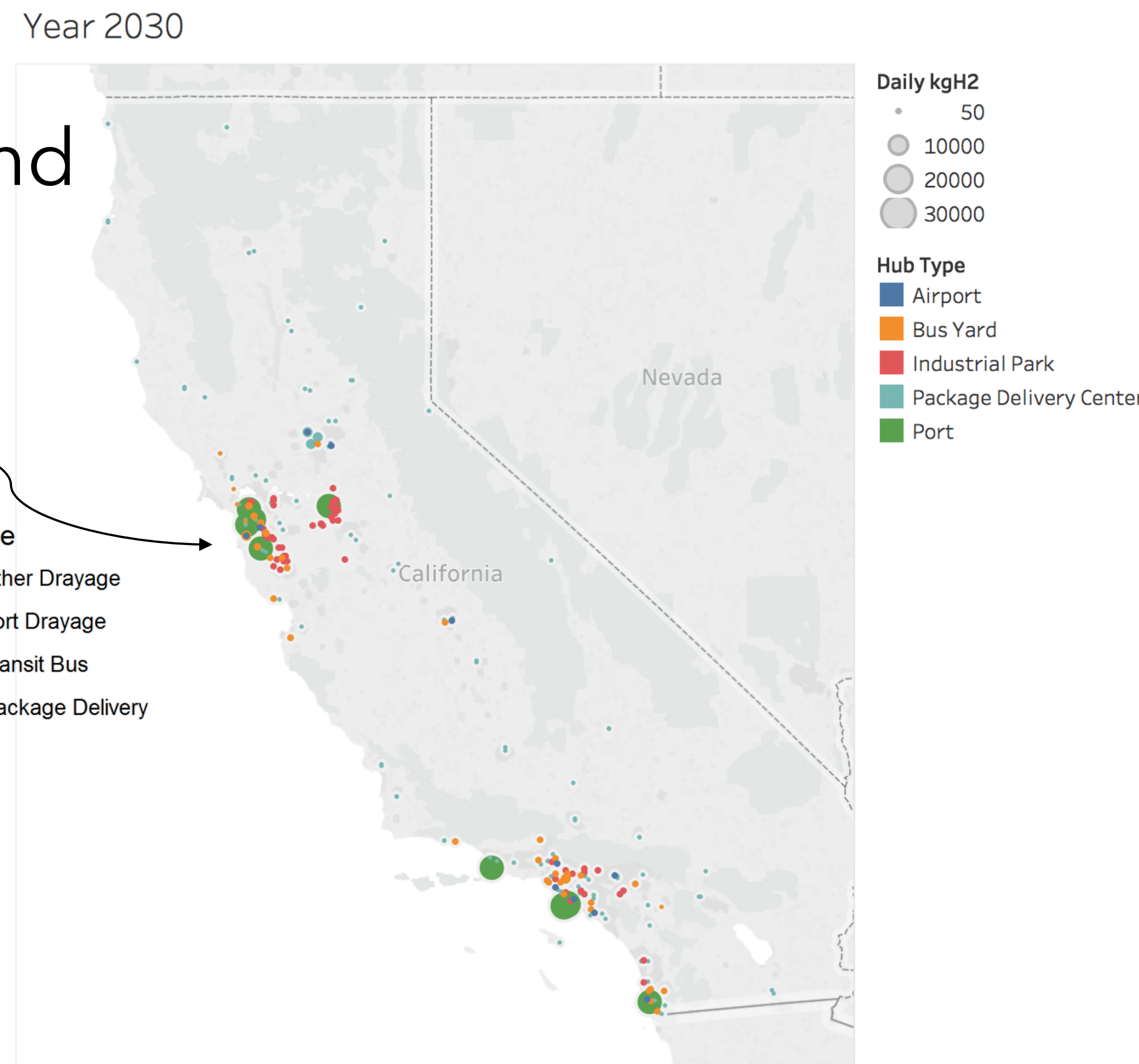
Local FCVs: H2 Demand





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.

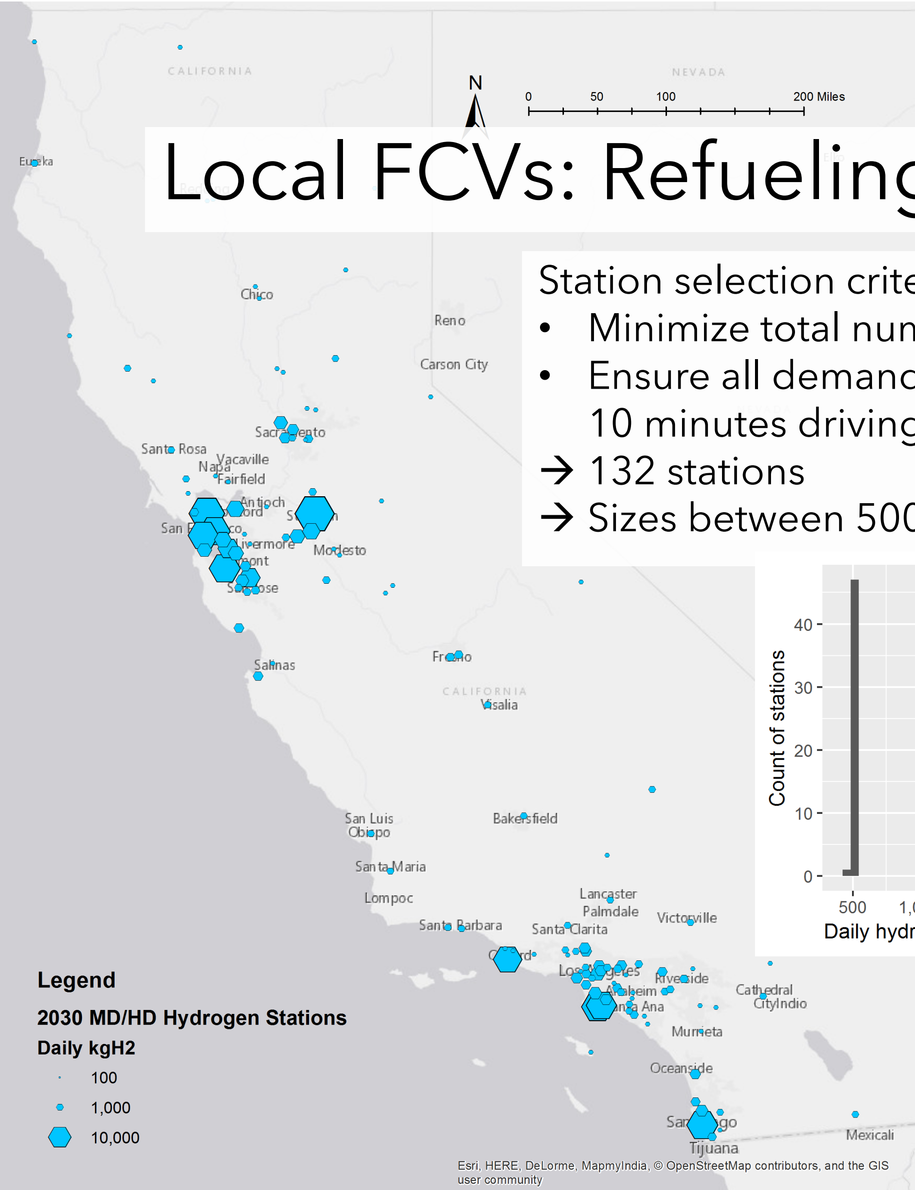
Local FCVs: Refueling Stations

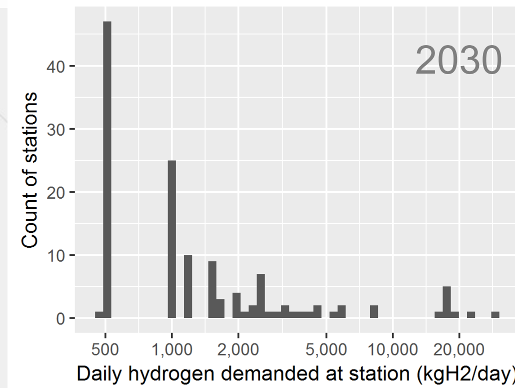
Station selection criteria:

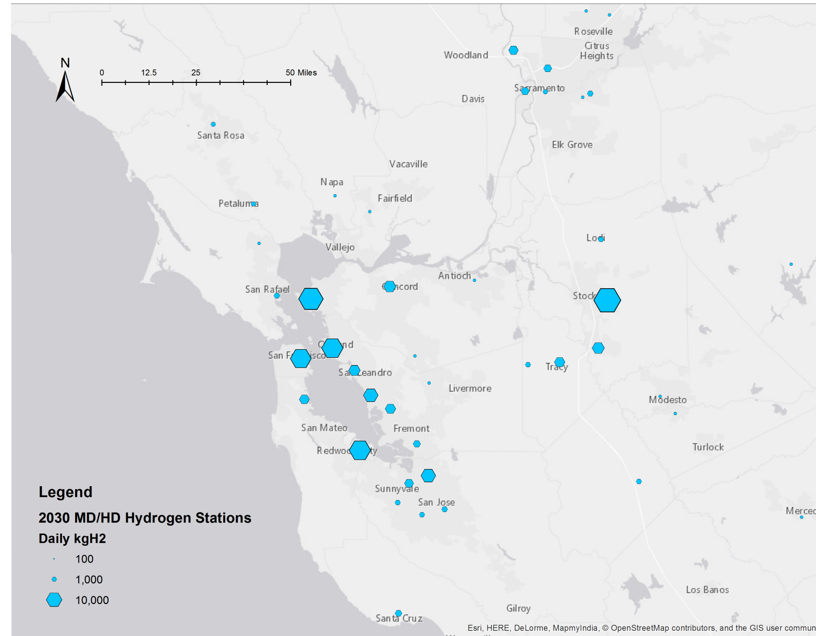
- Minimize total number of stations
- Ensure all demand points are within 10 minutes driving time to station

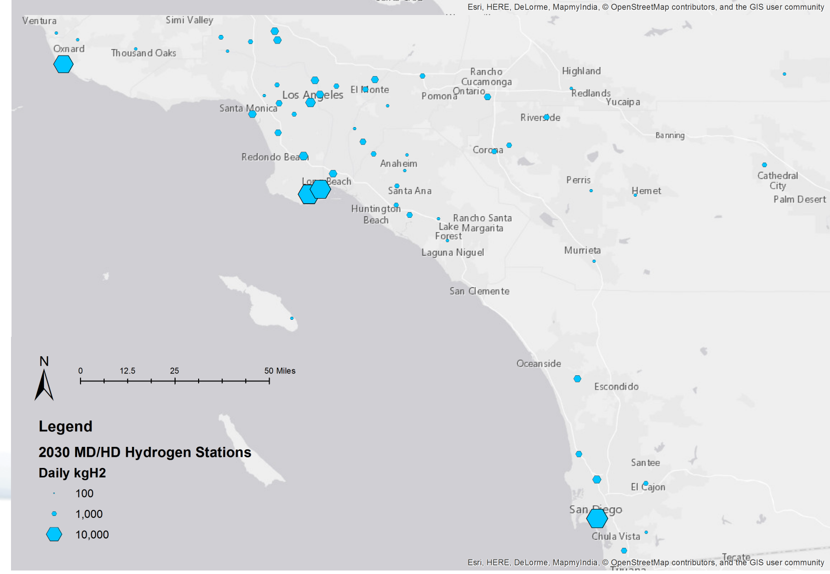
→ 132 stations

→ Sizes between 500~20K kgH2/day









Long-Haul FCVs

Truck Route Network

- Simplify California's truck route network
- Identify key trips

Refueling Network

- Refueling station locations
- Refueling station size estimates

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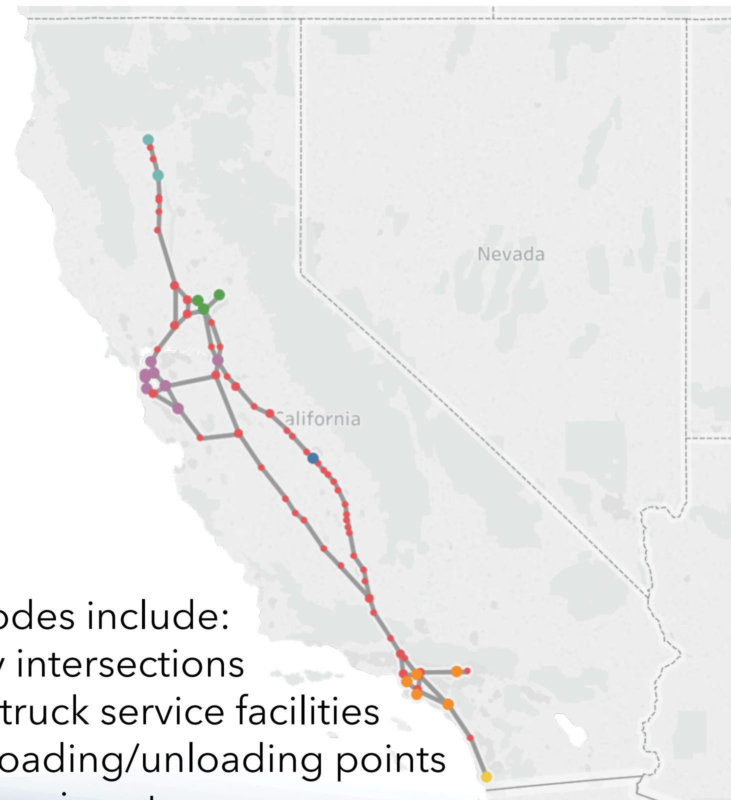
Long-Haul FCVs: Network

Actual Truck Routes

Simplified Truck Route Network



Network nodes include:

- Highway intersections
- Existing truck service facilities
- Freight loading/unloading points e.g. ports, airports

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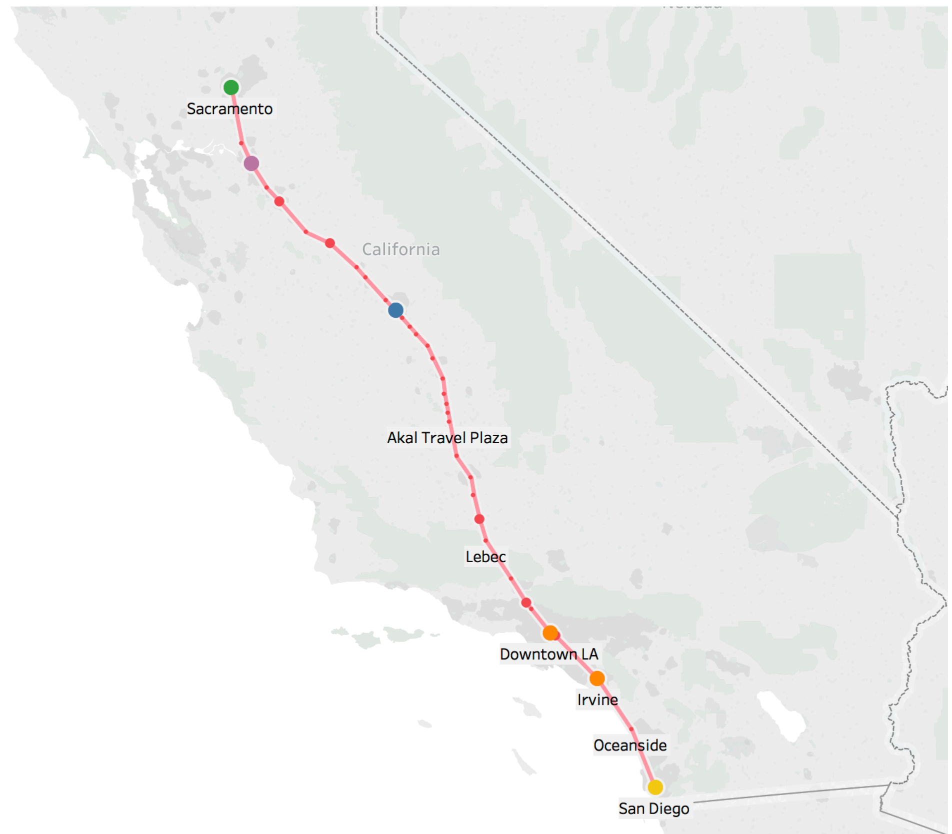
Long-Haul FCVs: Trips

- We choose 380 trips between California's major metropolitan areas
- Every trip takes the shortest path on our simplified truck route network
- We want all trips to be refuelable



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Long-Haul FCVs: Optimal Station Locations

- Assume limited FCV range of 150 miles

- Refuel all 380 trips
  (on any trip, an FCV is ensured to have a place to refuel before tank runs empty)

- Use least number of stations

→ Model as an integer programming problem

$$\text{minimize} \sum_{i=1}^{N} x_i \tag{1}$$

subject to

$$\sum_{x_j \in F_{t,i,R}} x_j \geq 1 \quad \forall t \in T, \forall i \in Q_t \tag{2}$$

where

N = total number of nodes/candidate sites

$x_i \in \{0,1\}$ are decision variables, $x_i = 1$ when node i is chosen as a refueling station location, and $x_i = 0$ when otherwise.

T = set of all trips

Q_t = set of all nodes on trip t

R = range of FCVs (maximum distance an FCV can travel after a full refuel)

$F_{t,i,R}$ = set of all nodes that can provide fuel for a vehicle with range R to travel to node i on trip t, without refueling in the middle

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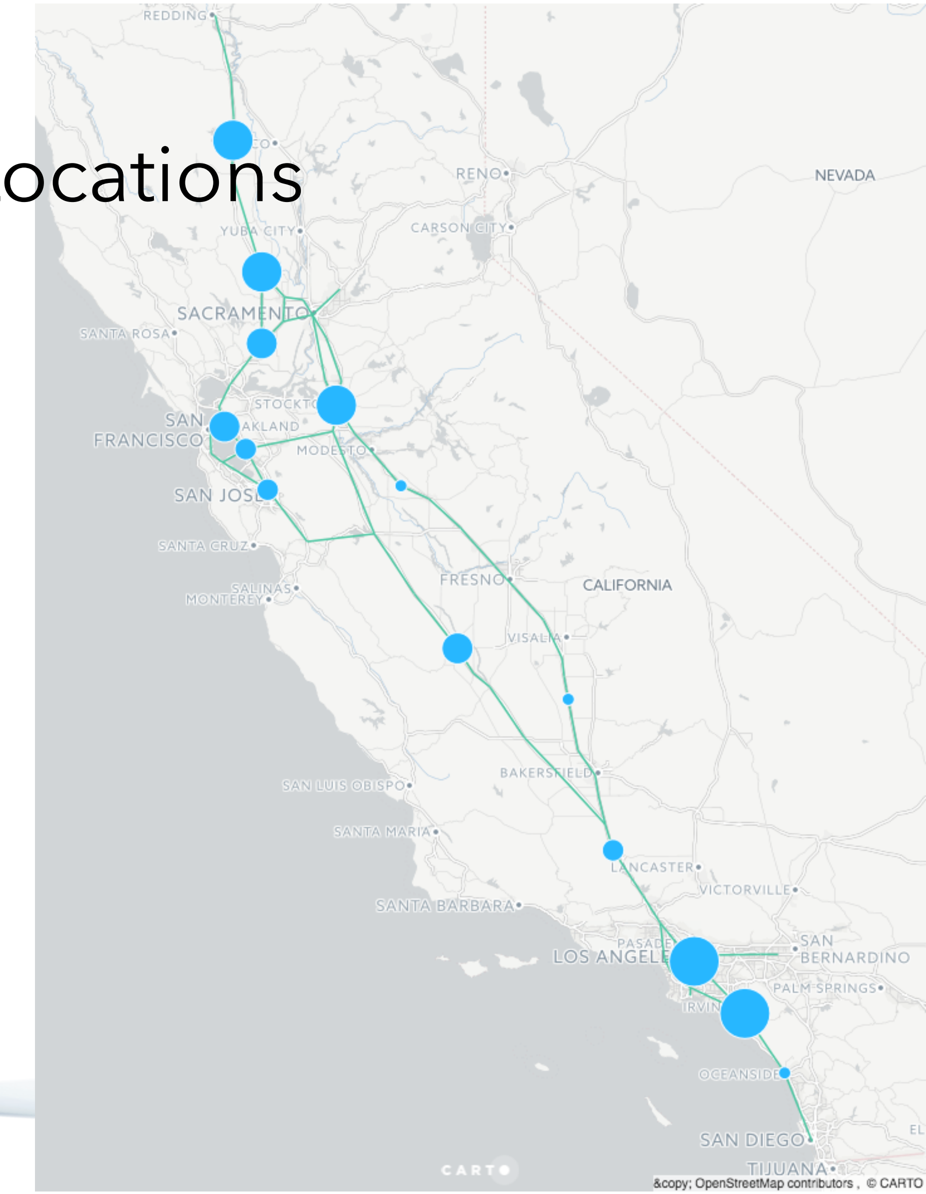
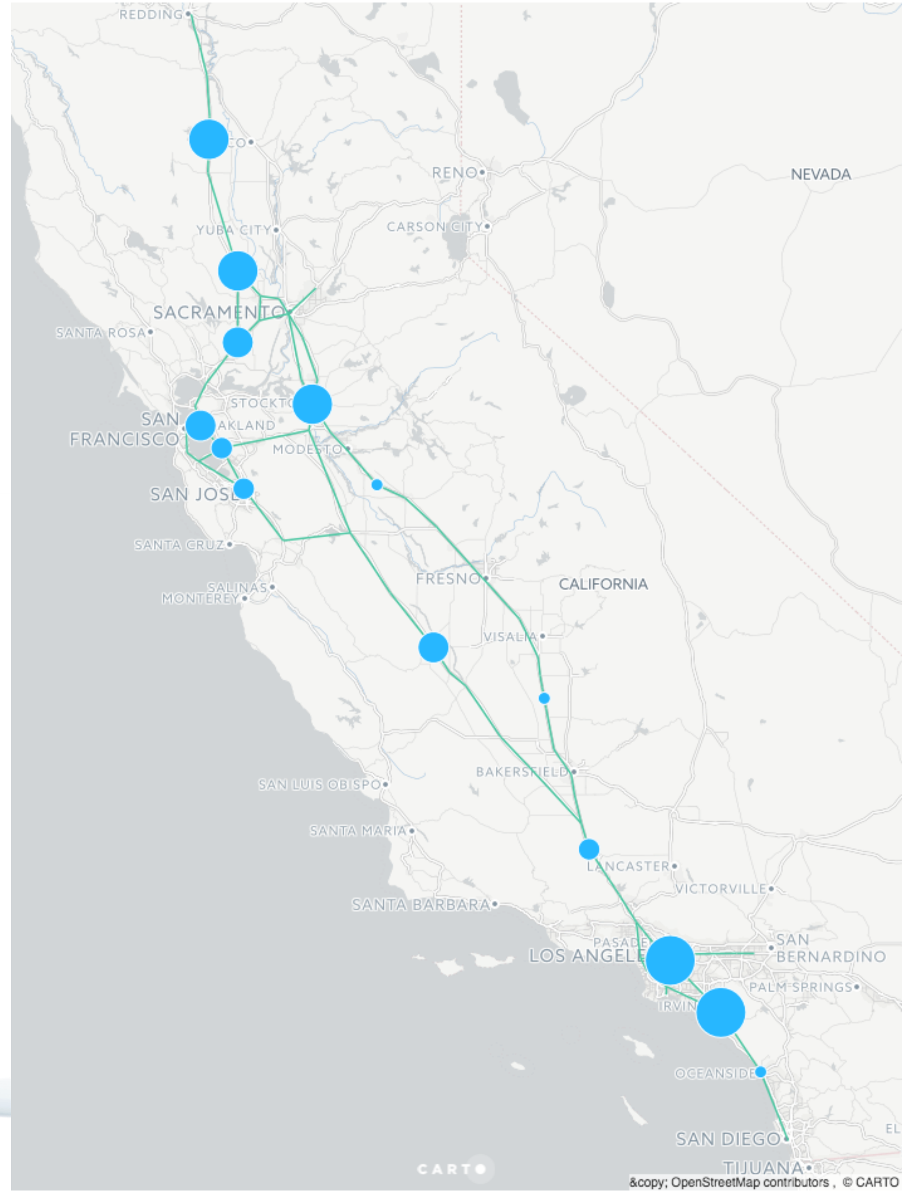
Long-Haul FCVs: Refueling Locations

- 14 refueling locations can cover the whole network
- Big city stations + connector stations in rural areas



Next Steps

- Integrate local and long-haul networks
- Include station cost in optimization
- Sensitivity analysis



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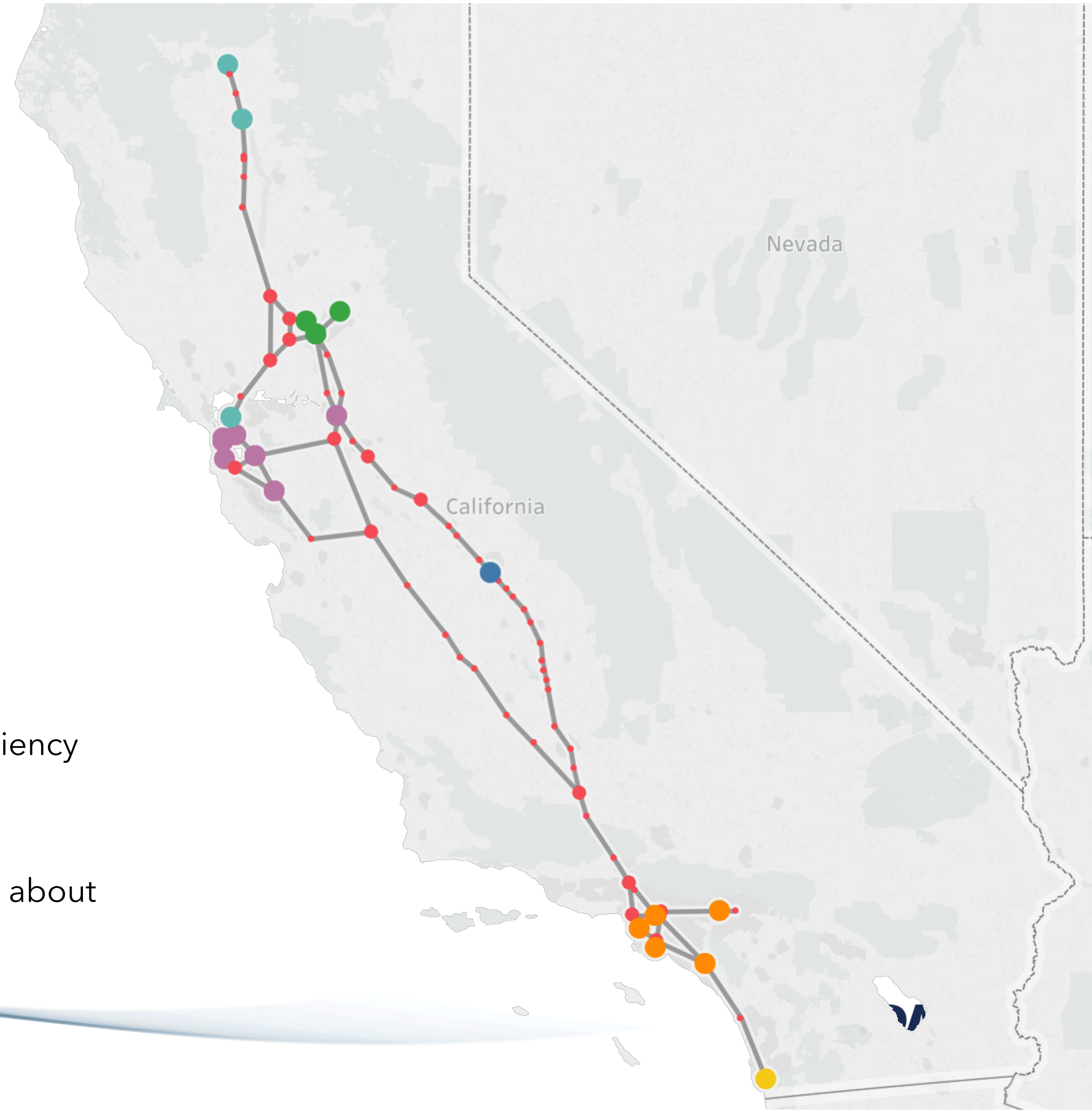

Acknowledgements

- Dr. Andrew Burke (UC Davis) for FCV fuel efficiency simulation data
- Mr. Michael Fries for truck daily mileage data
- Mr. Michael Britt (UPS) for sharing information about the fuel cell truck test program at UPS

Supporting Slides

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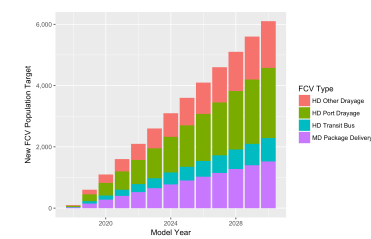
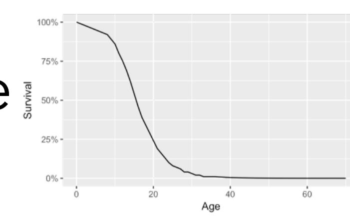
Two Markets

	Vehicle operations		Infrastructure
Local FCVs	• Return to hub • Small geographic area	→	Central refueling at hubs
Long-haul FCVs	• Large geographic area • Need en-route refueling	→	A state-wide refueling network

Local FCVs: How Many & Where

- For each analysis year (2018-2030), we assign the statewide new FCV population across the 200+ fleets
- Priorities are given to
  - "Seed" fleets in their "seed years"
  - Fleets already operating FCVs
  - Fleets near other FCV fleets
- Old vehicles die out following a survival curve





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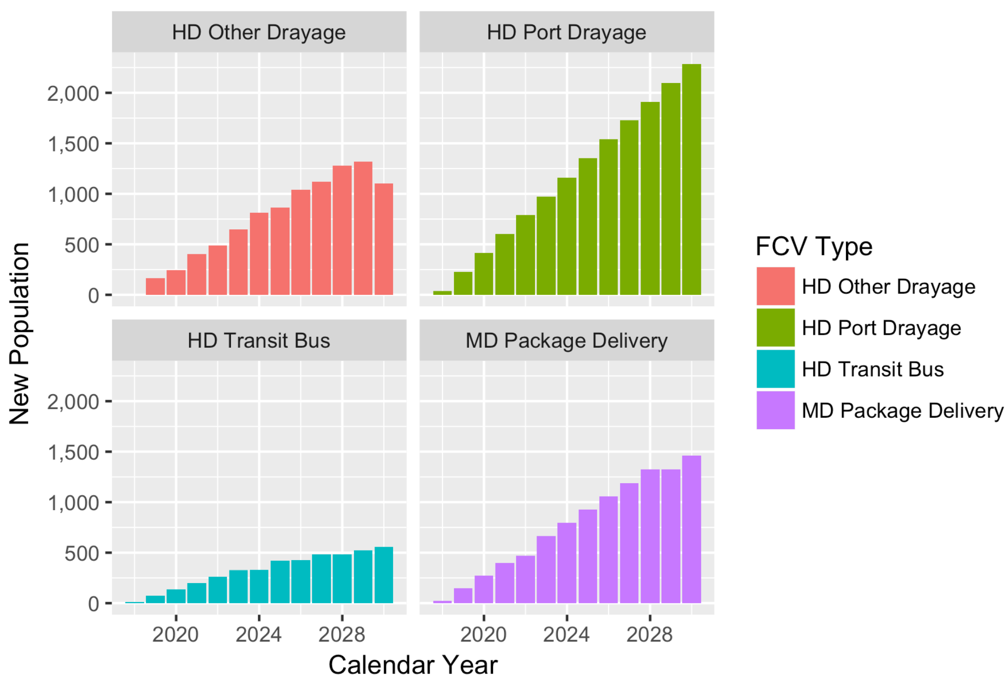
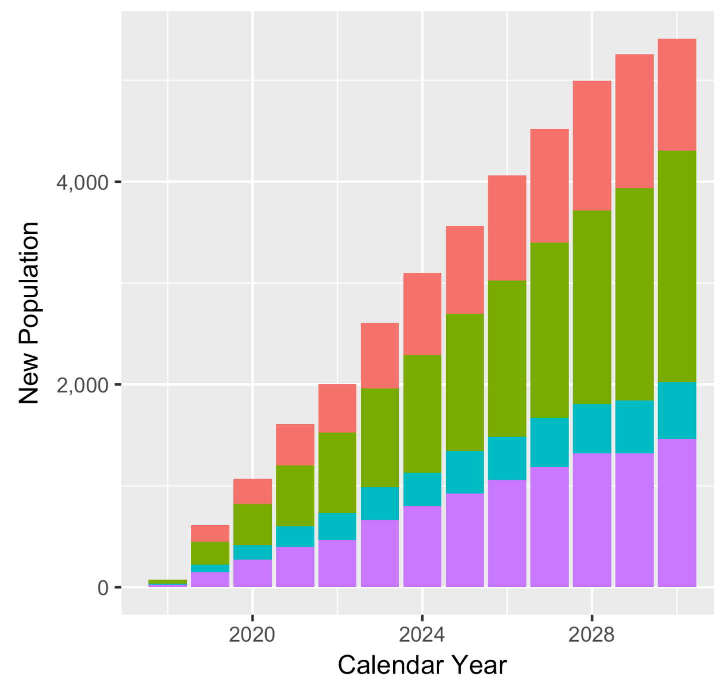
Local FCVs: New Population





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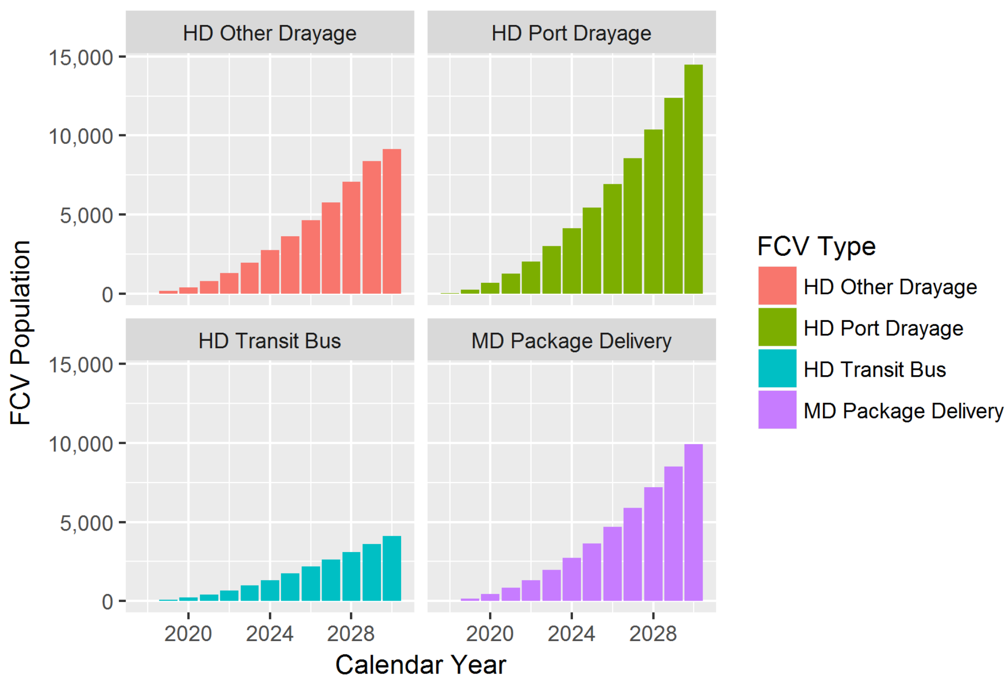
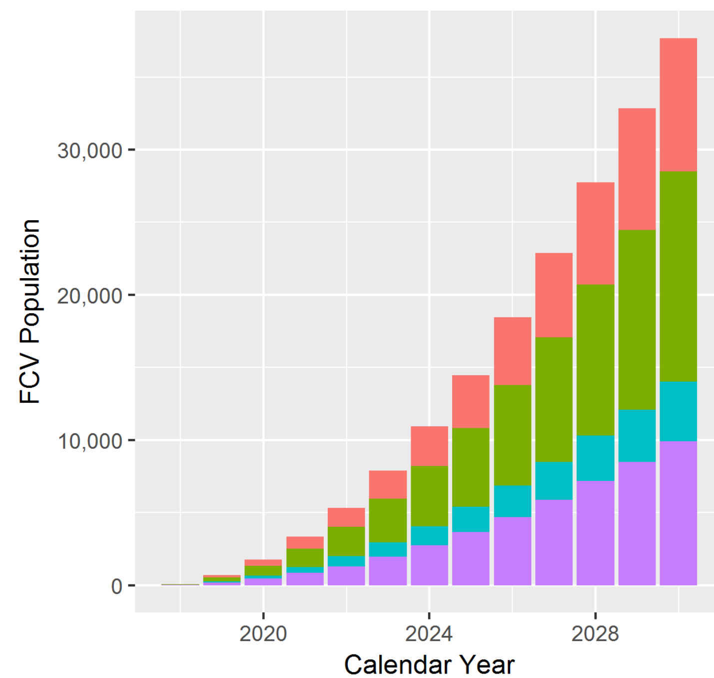
Local FCVs: Vehicle Stock





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Local FCVs: Vehicle Population → H2 Demand

Vehicle Population

(travel)
Average Daily VMT
→
150 miles /day/truck

(efficiency)
Average MPkgH2
→
Buses* 13.9
Package delivery* 20
Drayage 15

Daily H2 Demand
(kgH2/day)

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*: The fuel efficiency numbers are obtained from Dr. Andrew Burke's FCV simulation with the ADVISOR software.

Local FCVs: Fleets & Hubs data

- We collected a dataset of 266 potential FCV fleets/hubs
  - Ports (9)
  - Airports (12)
  - Package delivery centers (134)
  - Bus yards (42)
  - Industrial parks (69)
- For now we assume only 1 fleet at each hub (multiple fleets sharing a hub is also supported)

▼Fleets data snippet

fleet.name	base.hub	FCET_type	Seed_year	Fleet_size_cap
Port Drayage Trucks at Port Oakland	Port Oakland	HD Port Drayage		14000
Port Drayage Trucks at Port Long Beach	Port Long Beach	HD Port Drayage	2019	14000
Port Drayage Trucks at Port Los Angeles	Port Los Angeles	HD Port Drayage	2020	14000
Port Drayage Trucks at Port San Diego	Port San Diego	HD Port Drayage		14000
Port Drayage Trucks at Port Redwood City	Port Redwood City	HD Port Drayage		14000
Port Drayage Trucks at Port San Francisco	Port San Francisco	HD Port Drayage		14000
Port Drayage Trucks at Port Richmond	Port Richmond	HD Port Drayage		14000
Port Drayage Trucks at Port Hueneme	Port Hueneme	HD Port Drayage		14000
Port Drayage Trucks at Port Stockton	Port Stockton	HD Port Drayage		14000
Trucks at Bob Hope (Burbank) Airport (BUR)	Bob Hope (Burbank) Airport (BUR	HD Other Drayage		100
Trucks at Fresno Yosemite International Airp	Fresno Yosemite International Ai	HD Other Drayage		100
Trucks at John Wayne / Orange County Airpc	John Wayne / Orange County Air	HD Other Drayage		100
Trucks at Long Beach Municipal Airport (LGB	Long Beach Municipal Airport (LG	HD Other Drayage		100
Trucks at Los Angeles International Airport (L	Los Angeles International Airport	HD Other Drayage	2025	100
Trucks at Los Angeles Ontario International A	Los Angeles Ontario International	HD Other Drayage		100

▼Hubs data snippet

hub.name	hub.type	full.address	lon	lat	zip
Port Oakland	Port	1 Market St, Oakland, CA 94607	-122.2854	37.796529	94607
Port Long Beach	Port	Port of Long Beach, Long Beach, CA 90802, USA	-118.216458	33.754185	90802
Port Los Angeles	Port	Port of Los Angeles, Los Angeles, CA, USA	-118.260246	33.738009	90731
Port San Diego	Port	687 Switzer Street, San Diego, CA 92101-7810	-117.15652	32.698997	92101
Port Redwood City	Port	675 Seaport Blvd, Redwood City, CA 94063, USA	-122.209147	37.507674	94063
Port San Francisco	Port	Pier 80, San Francisco, CA	-122.379575	37.750239	94124
Port Richmond	Port	1411 Harbour Way S, Richmond, CA 94804, USA	-122.360593	37.913141	94804
Port Hueneme	Port	333 Ponoma St, Port Hueneme, CA 93041, USA	-119.200472	34.150879	93041
Port Stockton	Port	2201 W Washington St, Stockton, CA 95203, USA	-121.322365	37.945988	95203
Bob Hope (Burbank) Airport (BUR)	Airport	4699 W Empire Ave, Burbank, CA 91505, USA	-118.361026	34.19468	91505
Fresno Yosemite International Airport	Airport	5175 East Clinton Way, Fresno, CA 93727	-119.720755	36.767063	93727
John Wayne / Orange County Airport (	Airport	3000 E Airway Ave, Costa Mesa, CA 92626	-117.875112	33.671815	92626
Long Beach Municipal Airport (LGB)	Airport	4600 E Spring St, Long Beach, CA 90808	-118.140487	33.812015	90808

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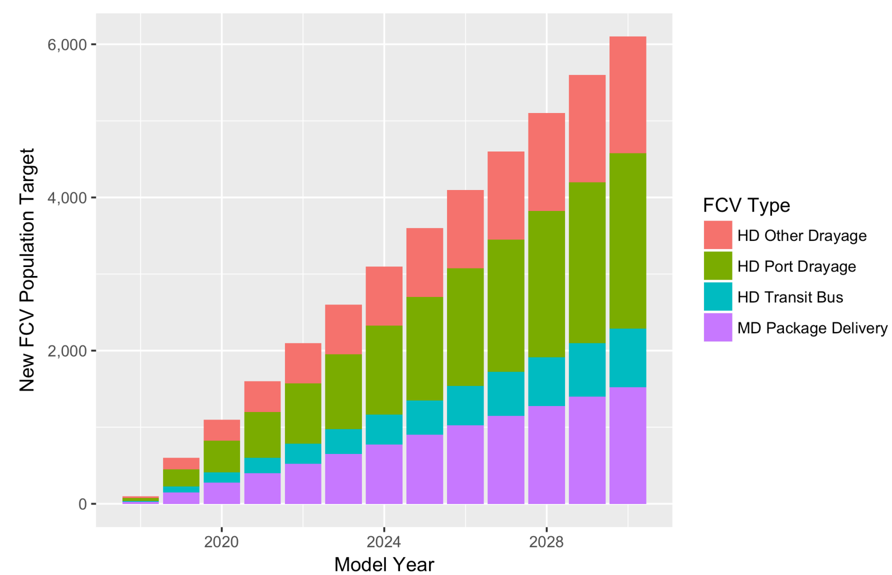
Local FCVs: Statewide Target

- State plan targets 100K zero-emission freight vehicles by 2030
- We assume ½ of these ZEVs are FCVs, that is 50K
- We assume 80% FCVs are locally operated
- That leads to the target of 40K local FCVs by 2030



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Local FCVs: New Vehicle Assignment

- Every year each fleet is assigned a score based on
  - If it is "seed" year of that fleet: 10 pt
  - If it already has FCVs: 8 pt
  - If it shares a hub location with other FCV fleet(s): 5 pt
  - If it is close to another FCV hub: 5-0.25*driving time to closest FCV hub in minutes (negative values are set to 0)
  - Final score is the highest of the above items.
- A high-score fleet takes how ever many FCVs of their desired type as they want, and the next high-score fleet comes in to do the same, until all available new FCV quota runs out.

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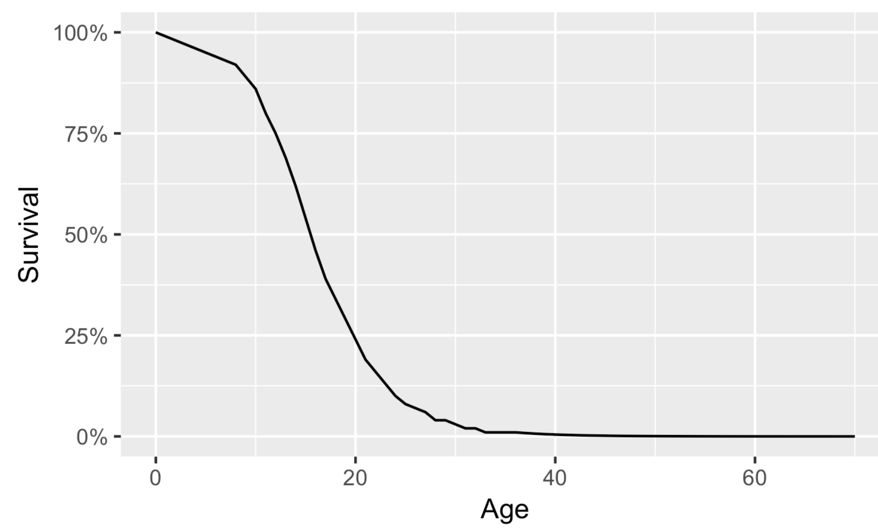
Local FCVs: Vehicle Survival Curve

- We adopt the survival curve from CA VISION database



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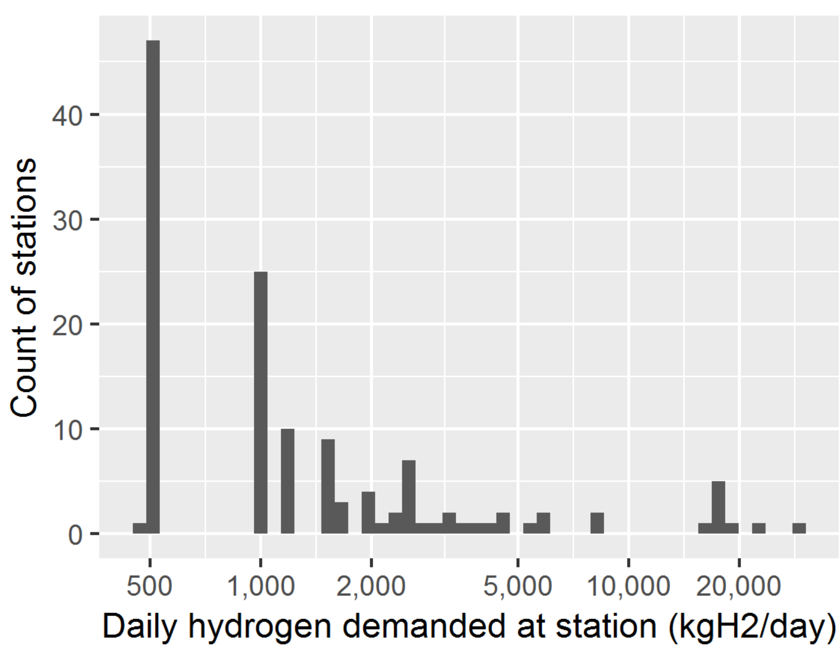
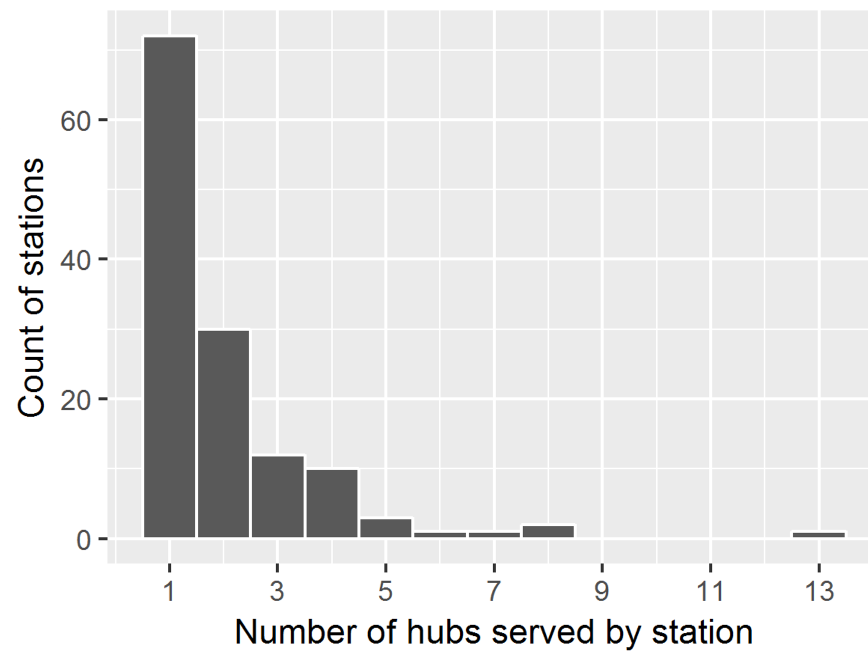
Local FCVs: Station Size Histograms





Long-Haul FCVs: The Route Network

- We hand-picked important points on CA's truck route network to be our network nodes
  - Intersections of major highways
  - Ports and airports
  - Existing truck service facilities
- The arcs represent actual roadway links between points
  - Arc length are driving distance measured with Google Maps API
- 75 nodes, 86 arcs

node_id	node_name	rank	lon	lat
1	Redding	1	-122.360642	40.58545
2	Red Bluff	1	-122.224084	40.179209
3	Dunnigan	2	-121.953458	38.860841
4	Woodland	2	-121.755159	38.689872
5	SMF	1	-121.59364	38.67109
6	Sacramento	1	-121.511491	38.567917
7	Roseville	1	-121.271214	38.743535
8	Elk Grove	3	-121.388703	38.408947
9	Lodi	3	-121.257655	38.117952
10	Davis	2	-121.767962	38.522138
11	Vacaville	2	-121.954351	38.372705
12	Richmond	1	-122.326836	37.935728
13	Oakland	1	-122.279569	37.800501
14	San Francisco	1	-122.4068	37.773857
15	Port of SF	1	-122.403985	37.748918
16	SFO			
17	San Jose			
18	Hayward			

arc_id	from_node_id	to_node_id	drive_dist_meters	drive_dist_km
1	1	76	9089	9
2	76	75	16778	17
3	75	2	21942	22
4	2	74	30458	30
5	74	73	2815	3
6	73	72	14581	15
7	72	71	25086	25
8	71	3	79684	80
9	3	4	26096	26
10	3	11	56868	57
11	4	10	21111	21
12	4	5	14976	15
13	5	6	16645	17
14	6	7	34251	34
15	6	10	31056	31
16	10	11	23248	23
17	11	40	41960	42
18	40	12	21726	22

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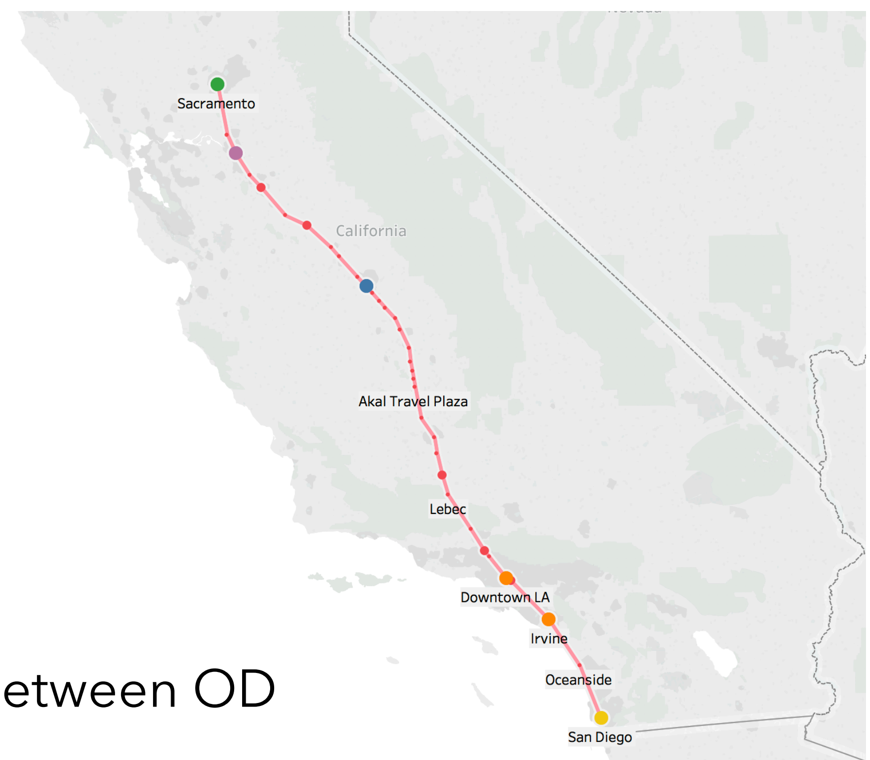
Long-Haul FCVs: The Long-Haul Trips

- Trips are between CA's major metropolitan areas:
  - Los Angeles area
  - San Diego area
  - Fresno area
  - San Francisco area
  - Sacramento area
  - Redding/Red Bluff area
- 20 nodes are OD nodes
- 380 trips
- All trips take shortest distance path between OD



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Long-Haul FCVs: Station Placement Algorithm

- Objective: minimize number of refueling stations
- Constraint: all 380 trips must be refuelable
- Formation: binary integer programming

$$\text{minimize} \sum_{i=1}^{N} x_i \qquad (1)$$

subject to

$$\sum_{x_j \in F_{t,i,R}} x_j \geq 1 \quad \forall t \in T, \forall i \in Q_t \qquad (2)$$

where

N = total number of nodes/candidate sites

$x_i \in \{0,1\}$ are decision variables, $x_i = 1$ when node i is chosen as a refueling station location, and $x_i = 0$ when otherwise.

T = set of all trips

Q_t = set of all nodes on trip t

R = range of FCVs (maximum distance an FCV can travel after a full refuel)

$F_{t,i,R}$ = set of all nodes that can provide fuel for a vehicle with range R to travel to node i on trip t, without refueling in the middle

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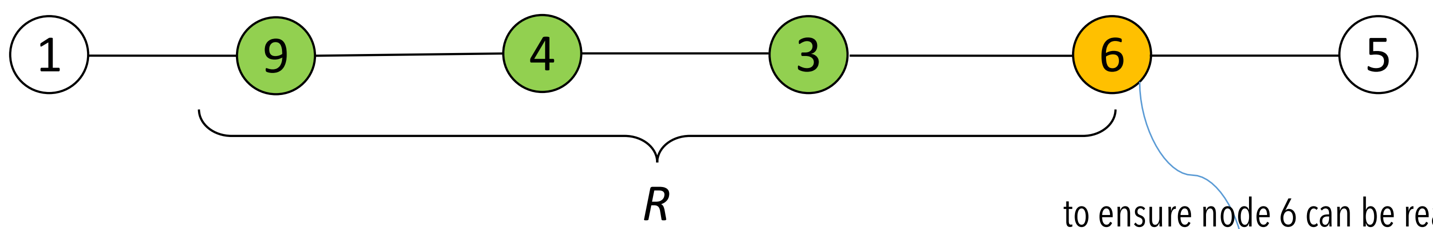
Long-Haul FCVs: Station Placement Algorithm

How to make sure all trips are refuelable?

- Make sure all node all trips can be reached without running out of fuel
- Each node on each trip leads to a linear constraint



to ensure node 6 can be reached

$$x_9 + x_4 + x_3 \geq 1$$

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Our Model Is Highly Customizable

You can customize

- FCV population growth assumptions
- FCV fleets and hubs. A hub can be shared by multiple fleets.
- FCVs' hydrogen VMT and fuel efficiencies
- Station coverage criteria (e.g. 5, 10, 15 minutes)
- Long-haul route network & candidate station sites
- FCV trips: ODs, paths
- FCV range limits

Our Model Is Only As Good As Its Input Data

We are looking for good data on…

- MD/HD fleet/operator info: location, fleet size, operation routes, etc.
- FCV specs: fuel efficiency, range, refueling speed, etc.
- Freight traffic data: ODs, routing, payload, refueling behavior
- H2 station costs (as alternative optimization targets)

Thank you!

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- Transportation & alternative fuels
- Data analytics / data science / data visualization
- Optimization
- Geospatial analysis