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Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery (ATLAS)

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Final Project Report for U.S. Department of Energy

Hydrogen and Fuel Cell Technology Office

Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery (ATLAS)

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Abstract

The goal of the "Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery" (ATLAS) project is to examine the costs and energy system impacts of using hydrogen (H2) fuel cell electric vehicles (FCVs) for medium-duty goods delivery applications, with human drivers and some degree of automated operation in the future. Direct goods delivery to residences and commercial operations is an expanding transportation element that has been growing at approximately 9% per year in recent years, with an estimated $343 billion global industry value in 2020.

Key findings from the project include:

- Fuel cell powered Class 6 delivery vans become cost competitive on a TCO basis with conventional delivery vans after 2030 in these simulated delivery networks;
- Class 8 fuel cell-powered drayage trucks become cost competitive with diesel trucks on a TCO basis after 2035 in both highway and urban drive cycle simulations;
- Supplemental fueling to extend depot-based fueling from existing and new satellite stations is important for 7.5kg H2 storage delivery vans in semi-rural networks;
- With either 1 or 2 satellite stations and 7.5kg of H2 storage, fuel levels get very low on the longer duty cycle range vehicles by end of shift, suggesting the need for significant levels of auxiliary fueling and somewhat broader station coverage;
- Supplemental fueling from existing and new satellite stations is still important for 10kg H2 storage delivery vans in semi-rural networks, where some routes cannot be completed based on central depot fueling only;
- Supplemental fueling from existing and new satellite stations is not needed for 15kg H2 storage delivery vans in the semi-rural networks simulated here; and
- Vehicle automation for Class 6 delivery vans is estimated to provide a 10% reduction in fuel use for a per-mile cost reduction of about $0.05, or an overall lifetime TCO reduction of about $5,000 relative to the non-automated fuel cell vehicles with the various hydrogen storage capacities.

1. Introduction

The goal of the "Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery" (ATLAS) project is to examine the costs and energy system impacts of using hydrogen (H2) fuel cell electric vehicles (FCVs) for medium-duty goods delivery applications, with human drivers and some degree of automated operation in the future. Direct goods delivery to residences and commercial operations is an expanding transportation element that has been growing at approximately 9% per year in recent years, with a projected $343 billion global industry value in 2020.

This growing goods delivery area, expected to expand by $50-60 billion over the next 5 years in North America, includes the following operations:

- Direct good delivery through medium-duty vehicles to residences and commercial locations (Amazon, UPS, FedEx, etc.) with new fleets of Class 3-5 electric-drive vans;
- Larger Class 6-8 trucks for port to warehouse deliveries and transfers between large distribution centers; and
- Additional applications of electric drive technologies through logistics centers including warehouse operations using short-haul heavy-duty trucks and forklifts.

The ATLAS project analyzes medium and heavy-duty goods delivery vehicles as well as hydrogen-fueling networks to support these goods delivery applications, with varying station capacities and geographic distributions for example large urban and suburban areas. The medium-duty vehicle (MDV) delivery fleets based on Class 6 box trucks are being modeled on example route networks using a route optimization platform known as Graphhopper. Heavy-duty Class 8 drayage trucks running on fuel cells/hydrogen are also modeled, to deliver goods from ports/airports to warehouse locations, for then further deliveries to final destinations.

As part of the project, key parameters related to the design of hydrogen fueling networks to support MDV and HDV goods delivery vehicles are also being developed through station modeling. Goods delivery networks are being designed based on logic from locations of warehouse/logistical sites and then a randomized set of commercial and residential locations for delivery on example routes. In future work, the project team is working toward a larger integration of hydrogen vehicle and station modeling and network analysis, coupled with large-scale agent-based transportation network models such as BEAM at the Berkeley Lab.

Key objectives of the project include consideration/estimation of:

1) Hydrogen infrastructure fueling station design and layout to support MDV delivery van operations in example urban areas through the H2Plan framework (400 – 5,000 kg/day stations in various configurations and operational strategies);

2) System operational outputs for example MDV goods delivery model runs in the simulations, including energy use metrics, operational outputs (miles traveled, route data, deadhead miles, etc.), and hydrogen station energy use and performance;

3) Cases with 100 to 200-mile range hydrogen fueled MDVs and 200-400 mile range HDVs compared with conventional alternatives;

4) Near-term and longer-term projected costs of hydrogen infrastructure/fuel and vehicle fleet operations, compared with other fuels;

5) Approximate capital cost investment needs for the various scenarios;

6) SMART (specific, measurable, attainable, realistic, and timely) project outputs and metrics; and

7) Key sensitivities and opportunities for cost reduction to bring down the total cost of operation of H2-powered FCVs for medium-duty goods delivery applications.

This final project report is organized as follows. Section 2 presents a literature review of the relatively sparse previous research in this topic area. In Section 3 a general overview of project modeling tools is presented. Next, initial project scenarios are described and summarized in Section 4. Section 5 describes the overall structure of the H2Plan module to compile and analyze project inputs, outputs, and analysis. Section 6 presents input values for the vehicles in the simulations. examines the plans for estimating energy use from the vehicles simulated in ATLAS. Section 7 describes a preliminary set of simulations, as an intermediate step toward the final simulation analysis. Next, Section 8 describes the hydrogen station performance and cost analysis used in the study. Section 9 describes the project scenario analysis for goods delivery route networks in the Sacramento and Amador County, California areas as the final analysis region. Section 10 includes Class 8 drayage truck simulation results. Section 11 presents additional analysis of the Class 6 delivery vans including the first-order impacts of vehicle automation. Finally, Section 12 includes final project key findings, conclusions, and potential future work.

2. Previous Research on Zero-Emission Goods Delivery Networks

A literature review has been conducted to examine previous research in this field of hydrogen powered delivery vans and drayage trucks. There are relatively few scholarly articles and a few other published works that are relevant to this effort. Some efforts focus on the air pollutant and greenhouse gas (GHG) emissions implications of fuel switching from conventional diesel fuel to hydrogen, along with electricity for hybrid battery-fuel cell designs, while others focus on performance aspects. These efforts are summarized in this section.

First, Lee et al. (2018) have conducted a life-cycle comparison of hydrogen fuel cell electric trucks (FCETs) and their conventional diesel counterparts in terms of energy use and air emissions. The primary results are that hydrogen FCETs reduce lifecycle or well-to-wheel (WTW) petroleum energy use by more than 98% compared to their diesel counterparts. The reduction in WTW air emissions for hydrogen FCETs fueled with gaseous delivery hydrogen ranges from 20-45% for greenhouse gases, 37–65% for volatile organic compounds, 49–77% for carbon monoxide, 62–83% for oxides of nitrogen, 19–43% for PM10, and 27–44% for PM2.5, depending on vehicle weight classes and truck types. The analysis also finds that with the current U.S. average electricity generation mix, FCETs tend to create more WTW sulfur oxide emissions than their diesel counterparts, due to powerplant emissions for hydrogen production and compression, but these would vary regionally based on the use of coal for power generation.

Next, the International Council on Clean Transportation (Moultak et. al, 2017) assessed the potential evolution of diesel, diesel hybrid, natural gas, fuel cell, battery electric, and overhead catenary-powered freight vehicles in the 2025–2030 timeframe. The scope of the effort consisted of a cost-of-ownership and life-cycle greenhouse gas emissions framework. They find that find that overhead catenary electric heavy-duty vehicles would cost approximately 25%–30% less, and hydrogen fuel cells at least 5%–30% less, than diesel vehicles to own, operate, and fuel in the 2030 timeframe, based on projected cost reductions. In the emissions comparison, for the U.S. the battery and fuel cell-based solutions realize large reductions by 2030 compared with diesel and diesel-hybrid powertrains, on the order of 60% for FCETs and up to 80% for battery vehicles based on smaller batteries and overhead catenary charging. They caveat these findings that large investments in infrastructure, however, are needed to realize these benefits.

Finally, with regard to real-world testing, the Center for Transportation and the Environment (CTE) has partnered with UPS to test a hybrid battery-fuel cell powered delivery truck with support from the U.S. DOE. The first phase of the project consisted of converting and demonstrating a single vehicle, with a second phase to convert and demonstrate 15 additional vehicles to fuel cell power. In the first phase, the initial vehicle was tested for 11 months in both Southern and Northern California in regular service in the UPS fleet. The vehicle achieved a maximum range of 169 miles using 8.76 kilograms of hydrogen, with a fuel economy of 15 miles per kilogram once the energy consumed from the battery is also considered. Also, in simulation results, the project team found that battery-powered delivery vans with 99 kWh of battery could marginally complete a hilly delivery route in the Berkeley/Oakland, California hills of 69 miles, but could not quite complete a flatter route of 100 miles in the Houston area. Fuel cell-battery hybrid configurations with 45 kWh of battery could complete these routes, whether coupled with either a 16kW or 32kW fuel cell system (CTE, 2021).

3. Overview of ATLAS Project Modeling Tools

This project is leveraged with the use of several modeling tools available through the national laboratories and that have previously been supported by U.S. DOE. These include those described briefly below, as well as other data sources from the academic literature and real-world demonstration and pilot projects.

Key modeling tools used in the project include:

- GraphHopper Route Optimization API: The Route Optimization API, one of many routing products developed by GraphHopper, is a widely used API for solving large-scale vehicle routing problems with a variety of vehicle and driver constraints. Its ease-of-use, low set-up cost, and customer support make it our solver of choice. The project team also acknowledges the collaboration with GraphHopper was assisted through the existing research agreement with the LBNL BEAM team. ATLAS uses GraphHopper to provide a collection of delivery locations and then obtains optimal routes for a network of vehicles. Using these routes, energy consumption and H2 station locations are then studied in detail.

- HDRSAM: The HDRSAM model from Argonne National Laboratory (ANL) provides a bottom-up cost, maintenance, and operational analysis of heavy-duty hydrogen stations. As input, the model considers station capacity and type (e.g., liquid, gaseous delivery, compression type, utilization profile), to compute capital cost, operating expenses, and price of dispensed hydrogen.

- H2FAST: The H2FAST model provides comprehensive financial analysis of various supply chain elements of hydrogen infrastructure. It makes rigorous estimates of corporate finance practices and projects competitive price points of value added in individual supply chain elements. In this project this model is used to interpret hydrogen station scenarios of sizing and operation to compute competitive price of hydrogen.

- FleetDNA: This is an extensive database of 1HZ frequency data collection of vehicle usage for various commercial services. Specifically, the database will be used to inform real world use of commercial vehicles including impacts of traffic conditions, road grades, and vocational kinetics (e.g., stop frequency, stop durations, acceleration, and speed between deliveries).

- T3CO (A.K.A FASTSim): This physics-based model is used in analyzing the second-by-second fuel consumption of different powertrain vehicles. It is commonly used with FleetDNA derived cycles to estimate the performance of the vehicles over specific conditions. This model would be used to estimate fuel consumption of vehicles which would inform their fuel storage state throughout their service region.

4. ATLAS Project Scenarios and Vehicle Routing and Network Simulations

To simulate MDV delivery van routes, the first step was collecting delivery location addresses. The project team explored the opportunity to collaborate with delivery services for such data; however, this was soon deemed infeasible due to privacy concerns. As a realistic alternative, the team decided to simulate delivery addresses by sampling addresses from county-specific resources. These resources included parcel boundaries available through county data sharing resources and a list of properties from the County Office of the Assessor.

Once the delivery addresses were sampled, it was necessary to convert the street address to geo-coordinates for use in routing optimization solvers. To do this, the team utilized Google Maps Geolocation API for its ease-of-use, low cost per batch request, and highest accuracy in comparison to competitors. A script was written to submit sampled delivery street addresses to the Geocoding API and return the resulting geocoordinates as a ".csv" file.

Once the delivery address geocoordinates in csv format was available, the input for GraphHopper was prepared. This included providing details of the delivery vehicles, maximum shift durations per vehicle, starting and ending depot position for delivery vehicles, and list of delivery geocoordinates along with vehicle dwell time at each location. An input parsing script was then developed to present this information from the csv to the required JSON format. The resulting JSON file was ready to submit to the GraphHopper API. Two Python language scripts ware developed to post this request and fetch the results from the API. The posting script required the use of the project team's API credentials and returned a job ID, which was used in the fetching script to obtain an output JSON file.

The output JSON file provided details of the optimal routes to the vehicle routing problem. This includes total distance traveled, time spent by each delivery van at each location and over its daily route, and list of delivery geocoordinates for each delivery van in chronological order, i.e., optimal route details for each vehicle subject to all conditions. We also use a simple script to convert this JSON output to a csv file that includes all relevant information for each individual route along with distance and time metrics at each delivery location. The GraphHopper output also includes a route network image with all routes for preliminary visual inspection. These are discussed in more detail in Section 4.

Before presenting details about the network scenarios considered, two important elements must be highlighted:

- Defining the objective function for GraphHopper input: GraphHopper enables solving the vehicle routing problem under a variety of objectives – minimum total completion time, minimum total distance traveled, and minimum number of vehicles used. For the purposes of ATLAS and to replicate real-life industry standards, the team elected minimum number of vehicles as the primary objective function and minimum completion time as the secondary (tie-breaking) objective. The reasoning behind this was to fully utilize each vehicle's availability for an 8-hour shift (instead of potentially using multiple vehicles for lesser time to reduce completion time/distance traveled) and then to assess the fuel-use patterns for vehicles traveling larger distances under different fueling scenarios.

- Use of dwell time at each delivery location: To simulate real world delivery networks, the team incorporates the element of stop-and-go time delay (called dwell time) associated with each delivery location. This is the time required for the delivery person to disembark, collect the parcel, and drop off at the required location. This dwell time is defined as a random variable from a normal distribution with mean 80 seconds and standard deviation 15 seconds. These metrics were identified from informal interactions with multiple delivery drivers regarding their average service metrics.

The initial ATLAS project considered two primary regional areas in Northern California: 1) a coastal area near a major port (San Francisco East Bay Area), and 2) an inland area approximately 100 miles from a major port (Sacramento and surrounding counties). These are intended to capture a range of geographic and transport network conditions (e.g., climate, hills, travel distances) but within a defined region that has an established and growing hydrogen fueling network. In particular, using methods described in Section 2, we collect addresses from Berkeley, Oakland, Piedmont, Emeryville, and Albany from Alameda County to study the first region of interest and from all cities in Sacramento County and Amador County to study the second region of interest. These regions are described in the figures below.

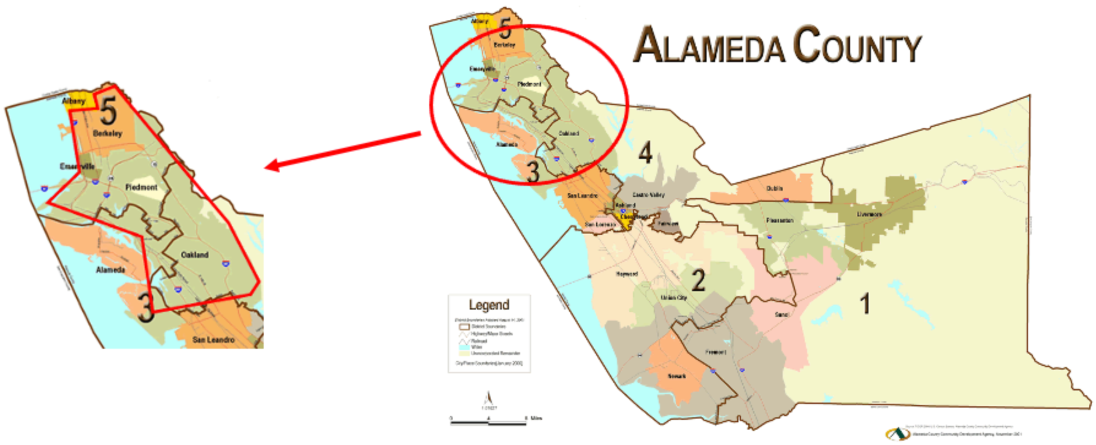


Figure 1: San Francisco East Bay Area – First Analysis Zone

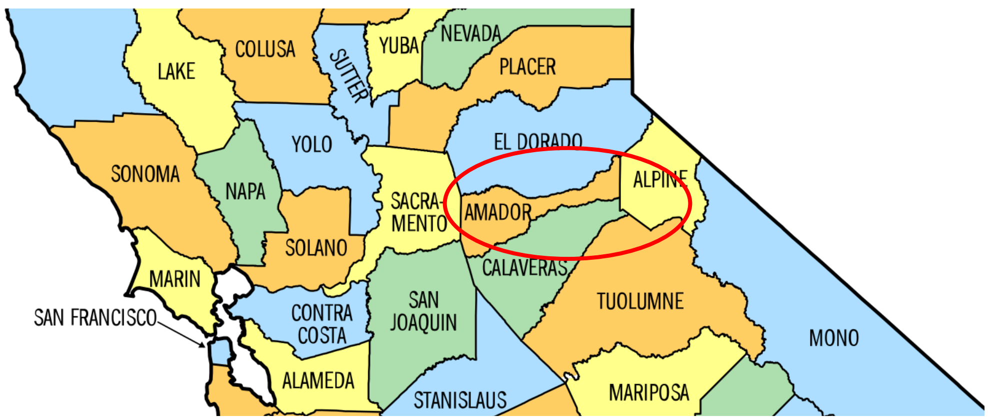


Figure 2: Greater Sacramento Region – Second Analysis Zone

Using the collected addresses, three route networks were simulated by sampling as follows, 1) 1,000 delivery addresses in East Bay region, 2) 1,000 delivery addresses in the city of Sacramento, and 3) 1,000 delivery addresses in Sacramento County and Amador County. As specified earlier, the variation in sampling regions and location helps to study network performance under different conditions and delivery vehicle distances; for instance, the delivery areas are compact in case 1 and 2, and large in case 3, whereas the topography is hilly in case 1 and 3, and flat in case 2. To further replicate a real-world scenario, all three networks originated from hubs in industrial locations in the region. In case 2 and 3, it is important to also note that delivery networks would be preceded by drayage truck deliveries for goods to then arrive at warehouse/fulfillment centers, likely traveling from the Port of Oakland (located in the San Francisco East Bay).

With all three scenarios, once the delivery addresses were sampled, they had to be formatted as inputs for GraphHopper. A snippet of this input is provided below:

```
{
    "objectives": [
```

```
    {
      "type": "min",
      "value": "vehicles"
    }
  ],
  "vehicles": [
    {
      "vehicle_id": "van-1",
      "shifts": [
        {
          "shift_id": "monday",
          "start_address": {
              "location_id": "sac_depot",
              "lon": -121.387451,
              "lat": 38.646637
          },
          "earliest_start": 0,
          "latest_end": 28800
        }
      ]
    }
  "services":[
      {
          "id": "visit_0",
          "name": "no_name",
          "duration": 87.0,
          "address": {
              "location_id": "visit_0",
              "lon": -120.7682415,
              "lat": 38.3497516
          }
      }
```

The highlighted sections above indicate (in order), objective function to minimize number of vehicles, starting location for each vehicle, maximum shift duration (in seconds), dwell time at delivery location, and coordinates of delivery location. This format was followed for each delivery vehicle and location to produce an input JSON file.

On submitting a routing request to GraphHopper through our script, the next step was interpreting the output obtained. The output consists of two elements: JSON file and network image. The JSON file included most information on which our fuel consumption analysis is conducted. A snippet of this output is provided below.

```
{
                "vehicle_id": "van-11",
                "shift_id": "monday",
                "distance": 196873,
                "transport_time": 14287,
                "completion_time": 20905,
                "service_duration": 6618,
                "preparation_time": 0,
                "activities": [
                    {
                        "type": "start",
                        "location_id": "sac_depot",
                        "address": {
                            "location_id": "sac_depot",
                            "lat": 38.646637,
                            "lon": -121.387451
                        },
                        "end_time": 0,
                        "distance": 0,
                        "driving_time": 0,
                        "preparation_time": 0,
                        "waiting_time": 0,
                    },
                    {
                        "type": "service",
                        "id": "visit_sac_287",
                        "location_id": "visit_sac_287",
```

```
        "address": {
            "location_id": "visit_sac_287",
            "lat": 38.4462708,
            "lon": -120.894989
        },
        "arr_time": 3380
        "end_time": 3455,
        "waiting_time": 0,
        "distance": 57777,
        "driving_time": 3380,
        "preparation_time": 0,
    }
```


The snippet contains information about the route for "Van 11", and the highlighted sections above indicate (in order), the total distance traveled (in meters) and time taken (in seconds) for completing Van 11's route, and then individually lists the stops made by the van in order, starting from the depot location and subsequently at all service locations, where it also identifies the arrival and completion time at the location and distanced traveled to reach the location.

Finally, we also obtain network images as shown below. These images are primarily helpful in visualizing the scope of the delivery network and identifying any obvious errors. Once confirmed by visual inspection, the results from the output JSON are compiled in a csv file to conduct the fuel consumption analysis described later.

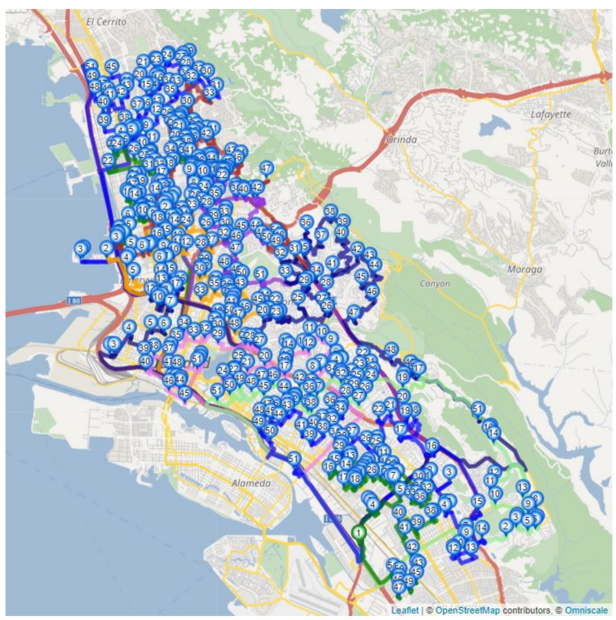


Figure 3: GraphHopper Optimal Routing Network for San Francisco East Bay Area (each color represents an individual route)

Graphhopper runs for this initial project were conducted using an online Graphhopper Route Editor API, while other more extensive APIs such as Insomnia (https://insomnia.rest) were investigated as well. Graphhopper requires a careful syntax in the json files for use in their API, as shown below and in Figure 4 in one sample of the beginning of the input code.

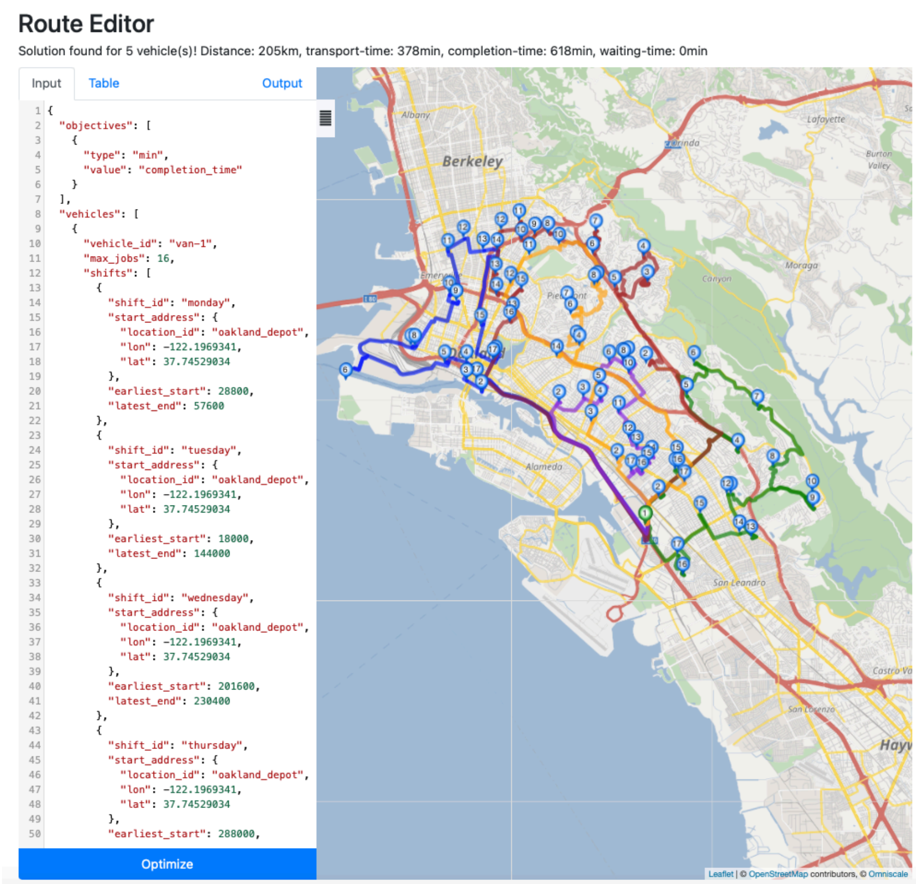


Figure 4: Graphhopper Route Editor API

Then, after processing through the Graphhopper Route Editor API, output files are produced also in “json” format as shown in Figure 5. Example json file outputs are shown below, including vehicle latitute/longitude coordinates, travel and wait times, travel distance, and driver shift information.

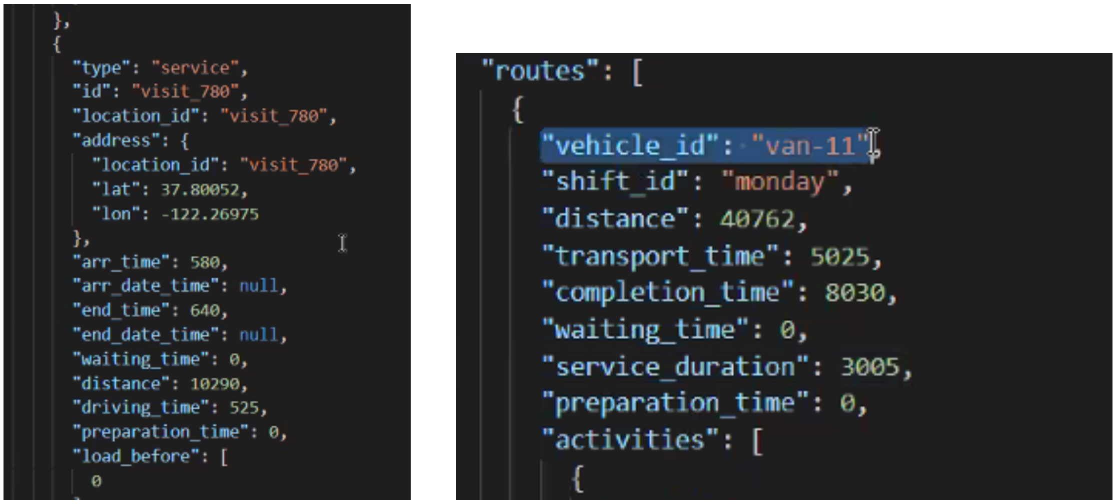
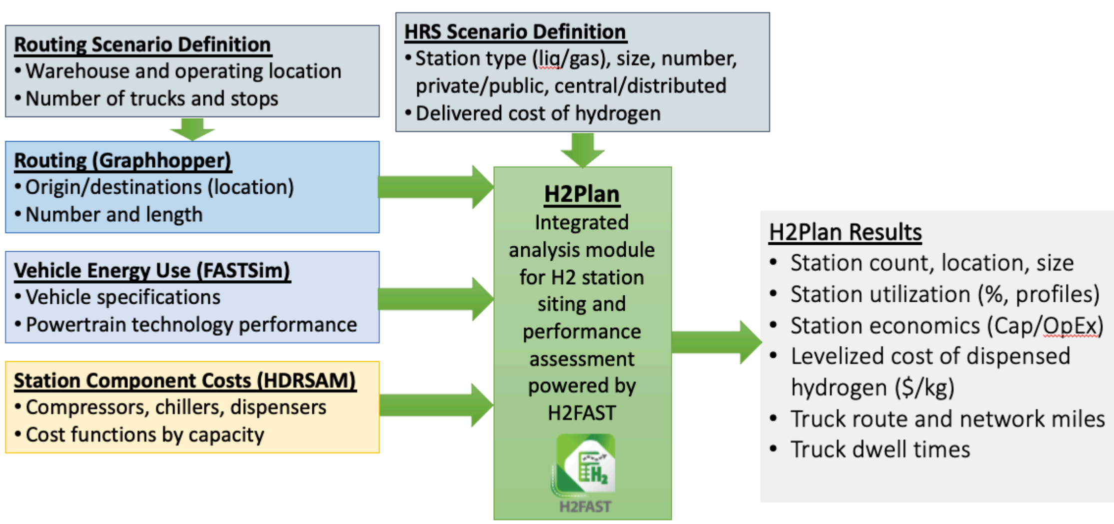


Figure 5: Graphhopper Example Output File Information

5. Development of H2Plan Framework for Project Analysis and Integration

The H2Plan spreadsheet framework connects various models being employed by ATLAS developed by NREL/LBNL/ANL with input and output data, as well as collecting overall project results for visualization through graphs and tables. H2Plan assimilates data and calculations for hydrogen station size and location by scenario, hydrogen station cost estimation, hydrogen vehicle duty cycle, hydrogen vehicle (delivery van and drayage truck) fuel usage and fuel cost, and hydrogen vehicle simple cost of ownership estimations. Figure 5 shows the high-level workflow for the H2Plan spreadsheet framework.



Source: LBNL/NREL

Figure 6: Overall H2Plan Framework and Workflow Schematic

A key element of the H2Plan module is to use Graphhopper route optimization outputs to pass an array matrix of a subset of output data, shown in Figure 4 above, from the Route Editor API to the vehicle energy use simulation aspects of the project described in Section 5 below. Graphhopper output array information includes: 1) the cumulative distance (kilometers/miles) driven by each MDV (delivery van) and HDV (drayage/hauling truck); 2) distance for each trip (kilometers/miles); and 3) the lat/long information for each vehicle origin/destination and delivery stops. These are then translated into estimates of vehicle fuel economy (miles/km per kilogram of hydrogen) and other key output metrics using the FleetDNA database and FASTSim as described in the following section.

6. Input Values and Assumptions for Simulations

For each of the two vehicle types analyzed – Class 6 delivery vans and Class 8 drayage trucks – various input values were selected for the simulations. These input values were derived from DOE technology evaluation efforts and were vetted by DOE HFTO staff prior to the simulations.

Common characteristics of vehicle power systems are shown in Figure 7, below. Detailed vehicle specifications for the Class 6 delivery vans are shown in Table 1. Additional characteristics of the vehicles are shown in a project simulation planning matrix in Appendix A.

	2025	2030	2040	2050
Fuel cell \$/kW	126	70	60	50
Fuel cell power (kW/kg)	0.7	0.8	0.9	1.0
Fuel storage \$/kWh	10	9	8.5	8
Peak FC efficiency	0.65	0.67	0.69	0.7
Fuel storage (kg)	30	30	20	20

Figure 7: Key Characteristics of Vehicle Power Systems

Additional further assumptions were made to facilitate the simulations. The most significant of these include that:

- fuel capacity for the Class 6 delivery vans was set to 7.5 kg, 10 kg, or 15 kg;
- the number of additional satellite stations was set to 1 – 6, with additional stations added incrementally in each simulation;
- Class 6 delivery van fuel economy was held constant at 17 mi/kg based on simulated results for flat driving;
- refueling threshold was set to be below 50% (vehicles search for fueling opportunities

under 50% capacity);

- distance from hub threshold was 5 miles (vehicles must be 5 miles away from the hub to search for fueling opportunities);
- fuel remaining threshold was 15% (vehicles plan to reach the hub with at least 15% remaining in the capacity and will look for refueling opportunities otherwise); and
- the maximum detour distance for refueling is 5 miles.

Further varying these assumptions and exploring different types of terrain (e.g., hilly areas) with appropriate grade modeling, and also variable weather/temperature conditions are relevant topics for future research.

Table 1: Key Input Parameters for T3CO Modelling of Class 6 Delivery Vans with Conventional and Fuel Cell Powertrains

Meta Data	Powertrain	Conv	Conv	Conv	Conv	FCEV	FCEV	FCEV	FCEV
	Model Year	2025	2030	2040	2050	2025	2030	2040	2050
Vehicle	Drag Coefficient	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
	Frontal Area (m^2)	9	9	9	9	9	9	9	9
	Vehicle glider mass (kg)	4528	4501	4501	4501	4528	4501	4501	4501
	Vehicle center of gravity height (m)	-0.53	-0.53	-0.53	-0.53	-0.53	-0.53	-0.53	-0.53
	Drive axle weight fraction	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Wheel base (m)	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
	Cargo mass (kg)	5083	5083	5083	5083	5083	5083	5083	5083
Fuel / Fuel Converter	Fuel storage power (kW)	5000	5000	5000	5000	5000	5000	5000	5000
	Fuel storage time to full power (s)	1	1	1	1	1	1	1	1
	Fuel storage energy (kWh)	3131	3131	3131	3131	337	337	337	337
	Fuel and fuel storage mass (kWh/kg)	12.67	12.67	12.67	12.67	1.8	2	2.1	2.2
	Fuel converter power (kW)	201	201	201	201	193.23	187.09	184.18	179
	Fuel converter time to full power (s)	6	6	6	6	5	5	5	5
	Fuel converter specific power (kW/kg)	0.23	0.23	0.23	0.23	0.7	0.8	0.9	1
Motor	Motor power (kW)	0	0	0	0	193.23	187.09	184.18	179
	Motor peak efficiency	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
	Motor time to full power (s)	4	4	4	4	4	4	4	4
	Motor controller mass (kg/kW)	0.39	0.22	0.17	0.08	0.39	0.22	0.17	0.08
	Motor controller base mass (kg)	0	0	0	0	0	0	0	0
Traction battery	Battery power (kW)	0	0	0	0	212.56	205.8	202.6	196.9
	Battery energy (kWh)	0	0	0	0	6.5	6.5	6.5	6.5
	Battery mass (kg/kWh)	4.18	3.3	2.57	2.25	7.78	5.83	4.67	4.38
	Battery base mass (kg)	75	75	75	75	75	75	75	75
	Battery round trip efficiency	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Wheels	Wheel inertia (one wheel) (kg m^2)	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
	Number of wheels	4	4	4	4	4	4	4	4
	Rolling resistance coefficient	0.00707	0.00662	0.00627	0.0058	0.00707	0.00662	0.00627	0.0058
	Tire radius (m)	0.516	0.516	0.516	0.516	0.516	0.516	0.516	0.516
	Wheel coefficient of friction	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Energy Mgt.	Minimum state of charge	0.05	0.05	0.05	0.05	0.1	0.1	0.1	0.1
	Maximum state of charge	0.95	0.95	0.95	0.95	0.8	0.8	0.8	0.8
	Speed where the battery reserved for accelerating is zero	60	60	60	60	60	60	60	60
	Percent of usuable battery energy reserved to help accelerate	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	Speed at which fuel converter is commanded on (mph)	55	55	55	55	1	1	1	1
	Power demand at which fuel converter is commanded on (kW)	100	100	100	100	100	100	100	100
Misc.	Alternator efficiency (conv. veh only)	1	1	1	1	1	1	1	1
	Auxiliary loads (kW)	2.23	2.06	1.83	1.5	2.23	2.06	1.83	1.5
	Force auxiliary loads on fuel converter (true/false)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
	Transmission mass (kg)	150	150	150	150	150	150	150	150
	Transmission efficiency	0.97	0.98	0.98	0.99	0.97	0.98	0.98	0.99
	Component mass multiplier	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Max regen	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

7. Preliminary Vehicle Energy Use Simulations Based on Estimated Vehicle Routes

Estimation of vehicle fuel use and individual hydrogen station usage was informed by use of a real-world representative cycle from FleetDNA. The cycle selection was informed by operational data collected on multiple class 5-6 parcel delivery vehicles throughout the US. The specific design cycle selected was from a whole day of operation of a vehicle, based on its representative total daily driving distance, stop frequency, kinetic intensity (measure of stop-and-go driving, speed).

Additional cycles were considered in the analysis to inform a maximum daily driving range encountered in the database, as well as cycles spanning larger number of stops, kinetic intensity, cargo loading, stops per mile and total work. The most representative cycle selected for this study had an average speed of 18 miles per hour and top speed of 68 miles per hour. Figure 8 below shows the speed versus time profile of the selected representative drive cycle as well as a histogram of speeds throughout its daily operation. The vehicle experiences highway speeds travelling to and from its service area, and predominantly operates at low speeds in its service area.

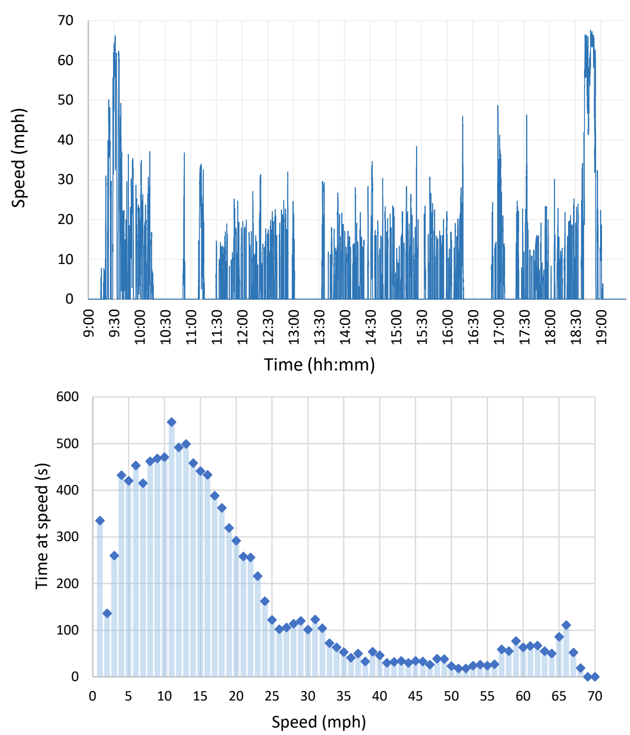


Figure 8: A Representative Driving Day for a Class 5-6 Parcel Delivery Truck

The described drive cycle was used to simulate vehicle operation using the T3CO model. The analysis used a vehicle model for Class 6 box truck derived from work on the Program Benefits Analysis (Reznicek, 2021). A conventional powertrain and fuel cell powertrain were simulated to allow benchmarking with measured performance specific to this class of vehicle use in parcel delivery vocations (Lammert, 2014).

Simulation of the specified vehicle models yielded similar performance on regulatory cycles (EPA 55mph, EPA 65 mph, EPA city) to those in the Benefits Analysis. However, benchmarking of results showed significant under-performance relative to fuel economy data reported in Lammert (2014). Review of the inputs and results identified two discrepancies in the model. The vehicle in the Benefits Analysis assumes the vehicles are fully loaded to their gross mass of 26,000 pounds by carrying over 11,000 pounds. This was significantly different than published results in Lammert 2014 of 4,000 pounds of typical cargo mass.

The Lammert (2014) study was the result of close collaboration with UPS, and its value of 4,000 pounds of typical cargo was supported by the industry partners due to low density of packages that are delivered, ability to extend vehicle life by not operating them at their mass limit, and ability to have significant weight margin to accommodate variations in cargo mass loading.

8. Hydrogen Station and Fuel Cost Analysis Summary

For hydrogen refueling station (HRS) cost estimation, an analysis has been performed using the Heavy-Duty Refueling Station Analysis Model (HDRSAM) from ANL. Additional hydrogen fueling economic analysis is conducted using the NREL H2FAST model.

The schema of the HRS is displayed in Figure 13 below, where we assume the stations to be delivered liquid hydrogen from Liquid Hydrogen Tankers (LHT) at 20K and 4-6bar. The liquid hydrogen is then stored into a cryogenic tank at the same temperature. The choice of a cryo-pump is made for LH2 pumping as it appears to offer high flow rates, low boil-off losses and significantly lower electricity consumption than gaseous compression (Petitpas and Aceves, 2018). After pumping, the Hydrogen is then evaporated to reach the cascade filling system pressure, to then be dispensed at 350 bar in the MDV tanks.

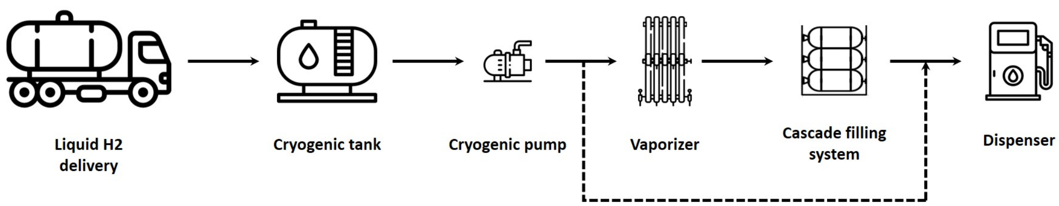


Figure 9: Schematic Representation of the HRS Design

The choice of operating at 350bar is based on the fact that the station will solely be used for MDV refilling, that hence need shorter range than LDV. Lower operating pressure allows for smaller equipment and decreased electricity consumption from pumping, that will result in smaller capital and operational costs.

The main scenarios involve considering various station capacities: 400kg/day, 1,600kg/day, 2,500kg/day and 4,000kg/day. The capacity of 400kg/day is representative of a small-scale station, whereas larger scale stations of 2,500 and 4,000 kg/day can be expected in the future. Those large-scale stations will most likely make sense from a financial point of view since they can benefit from economies of scale by amortizing the high CAPEX on larger quantities of delivered hydrogen.

Table 2: Outputs from HDRSAM modeling

Size [kgH2/day]	400	1600	2500	4000
Tank	$ 211 873	$ 399 769	$ 399 769	$ 788 792
Dispenser	$ 137 354	$ 274 709	$ 274 709	$ 412 063
Electrical	$ 73 284	$ 81 482	$ 89 085	$ 99 060
Cascade	$ 198 419	$ 297 628	$ 198 419	$ 297 628
Evaporator	$ 70 425	$ 224 955	$ 369 993	$ 564 173
Pump	$ 665 344	$ 1 330 688	$ 1 996 032	$ 2 661 376
Remainder	$ 100 000	$ 100 000	$ 100 000	$ 100 000
CAPEX ($)	**$ 1 456 699**	**$ 2 709 230**	**$ 3 428 007**	**$ 4 923 093**
Other CAPEX ($)	$ 335 041	$ 623 123	$ 788 442	$ 1 132 311
O&M (Less energy cost) [$/y]	$ 202 727	$ 325 348	$ 386 321	$ 540 791
Energy cost [$/y]	$ 4 512	$ 18 048	$ 28 199	$ 45 119
Electrical Energy Consumption (kWh)	45 119 kWh	180 476 kWh	281 994 kWh	451 190 kWh
LH2 Refueling Station Land Area (m^2)	1 383 m2	1 709 m2	1 709 m2	2 101 m2

After choosing the overall design and the key parameters that define the HRS characteristics, we then perform runs of the HDRSAM model. The model performs a bottom-up approach to size and cost each equipment. The aggregation of those costs provides a set of total initial uninstalled capital investment estimates. The model then estimates costs for site preparation, engineering, and all the operations & maintenance as a percentage of the capital cost to obtain the total capital investments (in $), the total yearly O&M (in $/yr) and the yearly electricity costs (in $/yr). Based on the design considerations, the model also estimates the required land area for the stations.

The ATLAS project initial runs of the HDRSAM model based on current assumptions allows to obtain the following estimates, shown in Figures 14 and 15.

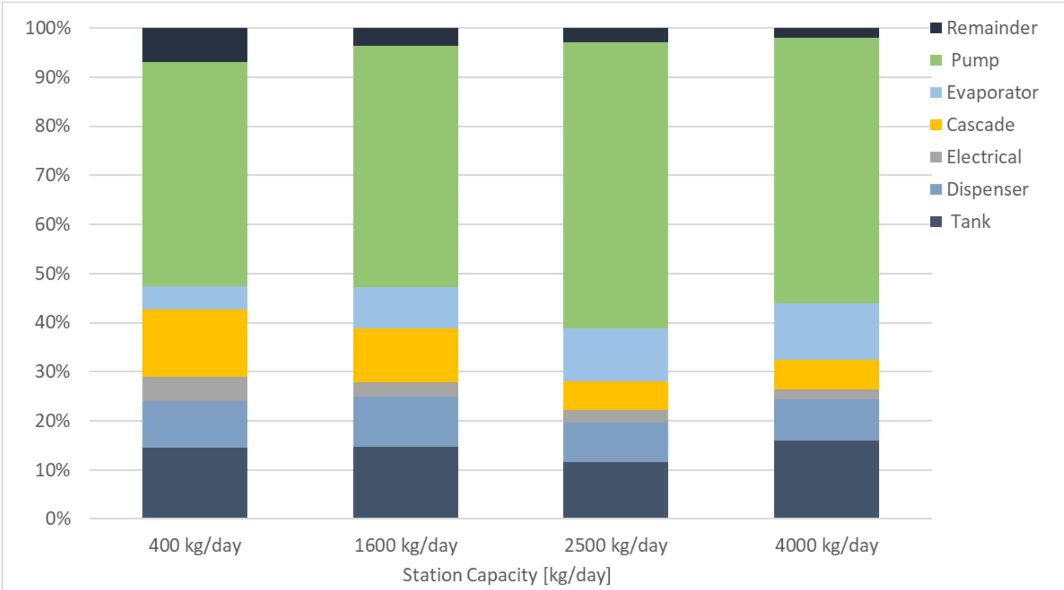


Figure 10: Decomposition of Capital Costs by Component for Each Station Size

Using the findings from HDRSAM, it is then possible to use NREL's H2FAST (Hydrogen Financial Analysis Scenario Tool) for financial analysis. H2FAST is designed to provide in-depth financial analyses for hydrogen fueling stations. Its interface allows to run efficiently a high number of scenarios to perform sensitivity analyses and will allow to output the break-even price of hydrogen provided various inputs: station capacity, capital costs, O&M costs, hydrogen and electricity consumption and costs, financial incentives, project lifetime, utilization rate, etc.

Table 4 provides a summary of the values used for the financial analysis using H2FAST in an example near-term case. Near-term levelized costs of hydrogen dispensed are also shown for the example station sizes.

Table 4: Estimates of Near-Term LCOH in H2FAST

Station Size	**400 kg/day**	**1600 kg/day**	**2500 kg/day**	**4000 kg/day**
Fleet size	20	80	125	200
Total VMT (miles/day)	2 000	8 000	12 500	20 000
Fuel economy	17 mpgge			
Dispensing pressure	350 bar			
Station Use rate	60%			
Delivered hydrogen cost ($/kgH2)	$ 6			
Total CAPEX	$ 1 791 740	$ 3 332 353	$ 4 216 449	$ 6 055 404
Annual O&M (less energy) ($/y)	$ 202 727	$ 325 348	$ 386 321	$ 540 791
Annual Electricity consumption (kWh)	45 119 kWh	180 476 kWh	281 994 kWh	451 190 kWh
H2Fast levelized cost of Hydrogen ($/kgH2)	**$ 12.75**	**$ 9.29**	**$ 8.75**	**$ 8.51**

For the overall ATLAS delivery network system analysis presented below, hydrogen costs were derived from H2FAST using similar assumptions shown in Table 4 and projected forward through 2050. The resulting fuel cost estimates are shown in Table 5 below. Also shown are comparison Diesel fuel costs for conventional delivery vans and drayage trucks, along with gasoline, CNG, and electricity costs for comparison.

Table 5: Estimated Future Fuel Costs for Project Analysis

	2025	2030	2040	2050
Diesel Fuel Cost ($/gal)	3.16	3.20	3.45	3.57
Gasoline Fuel Cost ($/gal)	2.73	2.91	3.20	3.32
Hydrogen Fuel Cost ($/kg)	7.72	5.68	4.42	4.42
CNG Fuel Cost ($/GGE)	1.62	1.50	1.47	1.41
Electricity Fuel Cost ($/kWh)	0.25	0.26	0.25	0.23

9. ATLAS Modeling Scenario: Sacramento/Amador California Region

For the final ATLAS project regional analysis, the Sacramento and Amador Counties region of California was selected. Preliminary analysis also included a denser urban area (the S.F. Bay Area), but delivery van distances were found to be relatively low, typically less than 100 miles per day, that likely could be adequately served with battery powered vehicles. A second region contained within Sacramento County showed considerably longer van driving distances than the S.F. Bay Area, but most routes were still under 100 miles and only one was over 125 miles on a simulated day. The project team initially hypothesized that hydrogen fuel cell delivery vans may find advantages where longer daily driving distances are needed, in mixed urban and suburban/semi-rural type areas that are more inland from the port regions in California, leading to the somewhat more semi-rural study area extending from Sacramento County to also including parts of Amador and El Dorado counties.

In this example, we assume that there is a goods warehouse on the North side of Sacramento, relatively near the Sacramento airport, where goods could be received through air cargo as well as ground transport. Figure 11 shows the location of the central delivery hub location near the main Highway 80 going through that part of town. For these simulations, goods are primarily delivered by Class 8 truck to the warehouse from the Port of Oakland and then the goods are delivered from the warehouse location to destinations in the surrounding area.

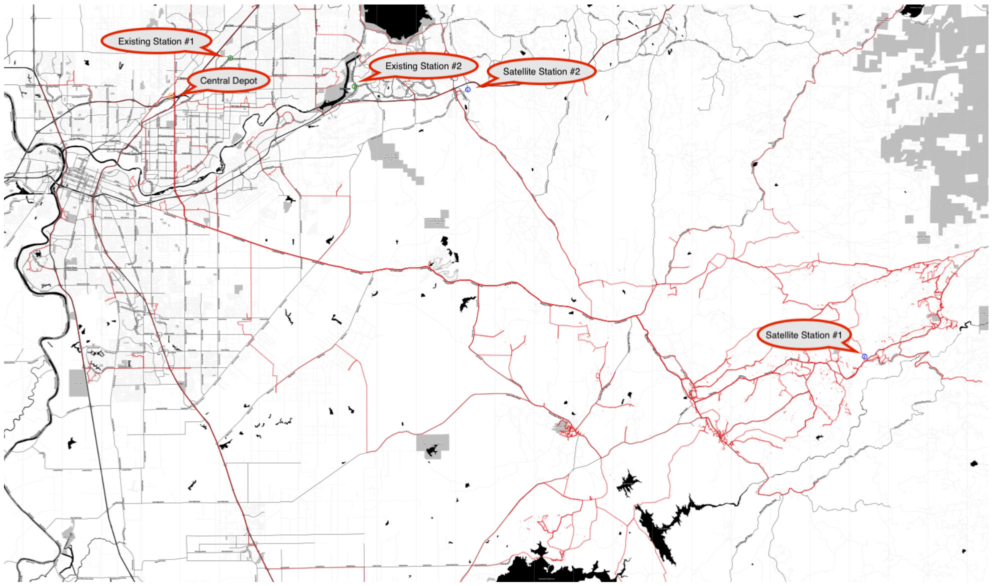


Figure 11: Sacramento, California Area Warehouse and Example Hydrogen Station Locations

The delivery routes are simulated in Graphhopper based on 8-hour shift lengths per delivery van. Based on the initial simulation of 1,000 delivery destinations selected for the simulation, and an estimated Poisson type distribution for the length of stops or "dwell times" at each stop location, 11 routes were identified as the optimal number to provide the necessary coverage. The characteristics of these routes are shown in Table 6 below. As shown, the shortest route has a distance of 100 miles and the longest had a distance of 211 miles. A few routes could be covered in less than a full 8-hour shift, with this result being generated because of the overall simulation constraint to minimize total delivery times as the primary objective function, along with minimizing the total number of needed vehicles as well.

Table 6: Outputs from Graphhopper Route Optimization for Sacramento / Amador Area Goods Delivery Van Network

Vehicle ID	Completion time (hh:mm:ss)	Distance(km)	Distance (mi)
Van 4	7:06:54	238.96	148.48
Van 9	7:02:04	241.56	150.10
Van 10	7:57:26	339.98	211.25
Van 11	5:48:25	196.87	122.33
Van 13	7:58:30	265.53	164.99
Van 14	7:45:43	281.72	175.05
Van 15	7:29:45	232.74	144.61
Van 17	4:42:44	161.57	100.39
Van 18	7:56:42	268.28	166.70
Van 19	7:56:16	263.86	163.96
Van 20	7:52:54	331.66	206.08

Note: Driving Time is the actual time that the delivery vans are in motion and Completion Time is the total time needed to complete the daily route including dwell times at the stop locations. Delivery van drivers are assumed to drive a 9-hour shift with an hour for lunch and breaks, for 8 hours of actual work time.

The various optimized delivery van routes are shown in Figure 12. As shown, some of the routes are fairly compact, but all of them involve more than 100 miles of daily driving, 7 of them are over 150 miles, and 2 of them are over 200 miles. Table 7 presents further details of the 11 delivery routes including the number of stops, the driving distance, the shift duration, and the estimated hydrogen fuel use in FASTSim.

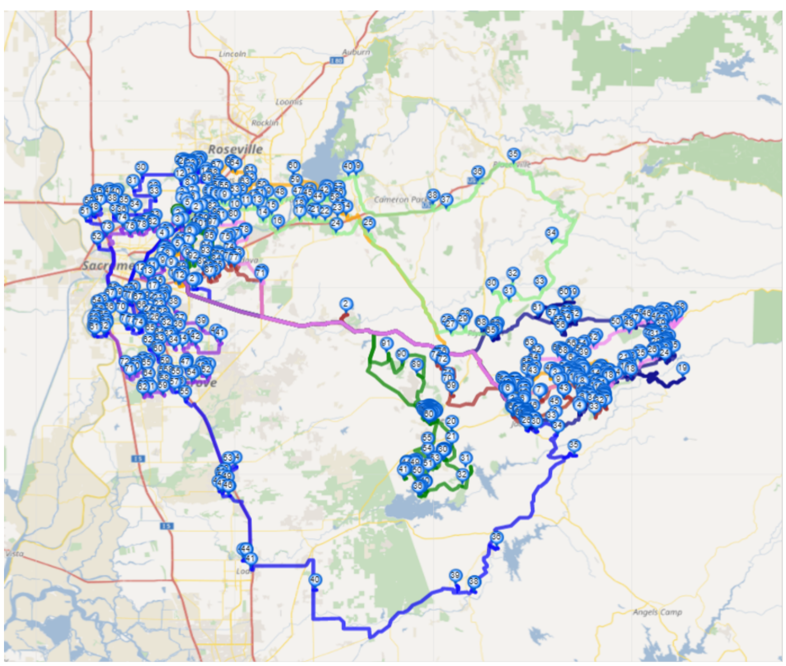


Figure 12: Optimized Route Network for Sacramento/Amador Area Goods Delivery Vans on Example Day Based on Randomized Delivery Locations

Table 7: Estimated Hydrogen Fuel Use by Route for Daily Fuel Cell Delivery Van Operations: Sacramento/Amador Region

Route ID	Number of Stops	Distance (mi)	Duration (h)	Fuel use (kg)
1	89	148	7.1	8.7
2	87	150	7.0	8.8
3	60	211	8.0	12.4
4	85	122	5.8	7.2
5	103	165	8.0	9.7
6	89	175	7.8	10.3
7	109	145	7.5	8.5
8	74	100	4.7	5.9
9	87	167	7.9	9.8
10	110	164	7.9	9.7
11	72	206	7.9	12.1

In this scenario, the average fuel use per vehicle is 9.37 kg per day and the total for all 11 delivery vans is 103 kg in this simulation. With only depot fueling available, 100% of the hydrogen fueling is depot-based, but some vehicles cannot complete their routes with 10 kg of onboard storage, necessitating the usage of at least one additional station.

The project analysis allows for the identification of additional satellite stations beyond depot refueling, where the given fuel cell delivery van driving range may be insufficient to complete one or more routes with depot fueling only. The ideal location for the additional station(s) in these scenarios are determined by genetic algorithm, based on the network of routes. The project analyzed three onboard hydrogen storage cases (7.5kg, 10kg, and 15kg) as well as the addition of up to 6 new “satellite” hydrogen stations along with the assumed central depot fueling station and two nearby existing hydrogen stations in this area of Sacramento.

With the assumed hydrogen tank capacity of the delivery vans of 10 kg, and the availability of one satellite station, 4 of the delivery vans can complete their routes based on central depot fueling and their daily driving ranges of 150 miles or less, as shown in Figure 13. Six of the delivery vans can take advantage of the satellite station to refuel in route, thus easily completing their daily operations. One van cannot take advantage of the optimized location of the single satellite station and returns to station with negative fuel level, meaning it could not complete its route in this simulation.

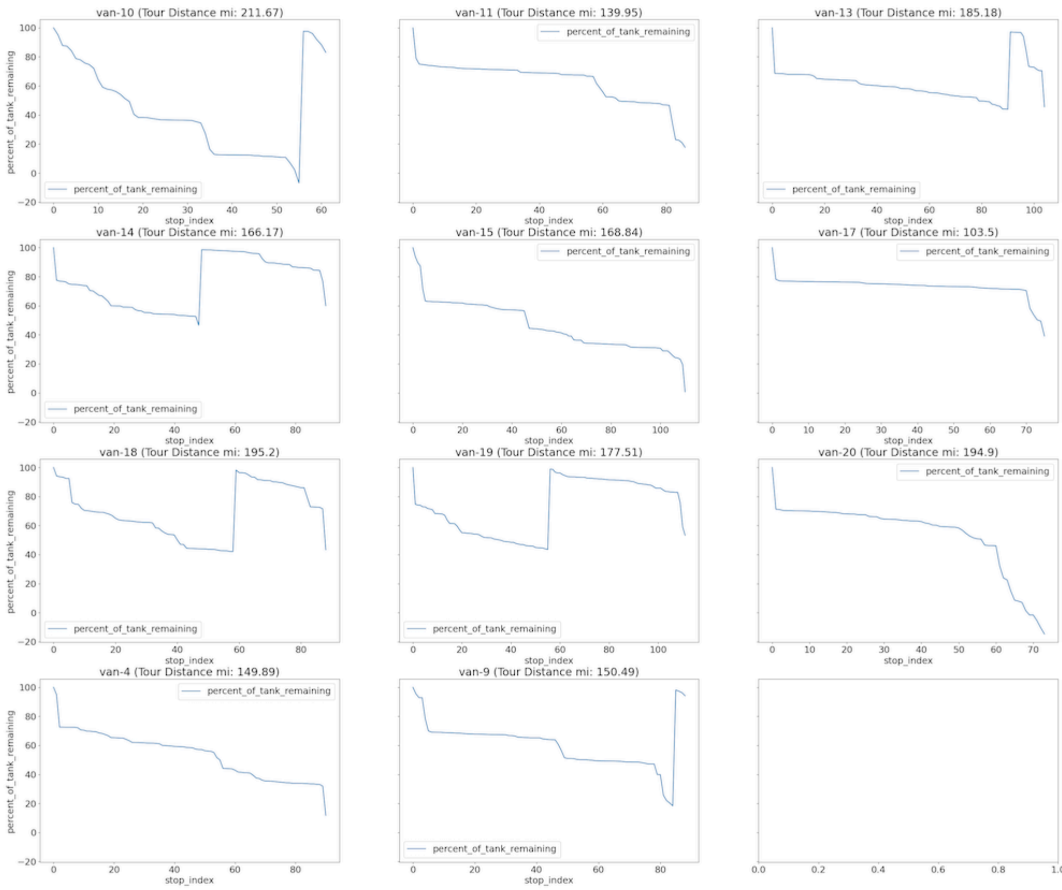


Figure 13: Hydrogen Storage Levels for Simulated Delivery Van Routes: 10kg of Onboard Storage, 2 Existing and 1 Additional Satellite Fueling Stations

As shown in Figure 14, the additional satellite station is used most heavily to complement the depot fueling, with two existing stations located relatively close to the depot also being used to a lesser extent.

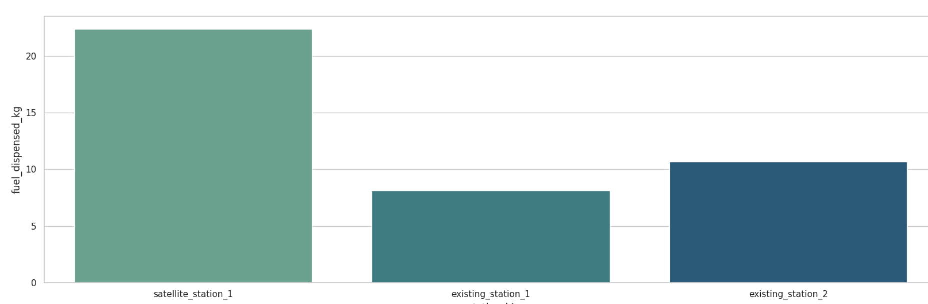


Figure 14: Hydrogen Station Usage for Simulated Delivery Van Routes: 10kg of Onboard Storage, 2 Existing and 1 Additional Satellite Fueling Stations

When a second satellite station is added in this case with 10 kilograms of onboard storage, both satellite stations are utilized and one of the existing stations is not utilized. Figure 15 shows the locations of the central depot (yellow circle), the two existing hydrogen stations (green circles), and the two satellite stations (blue circles).

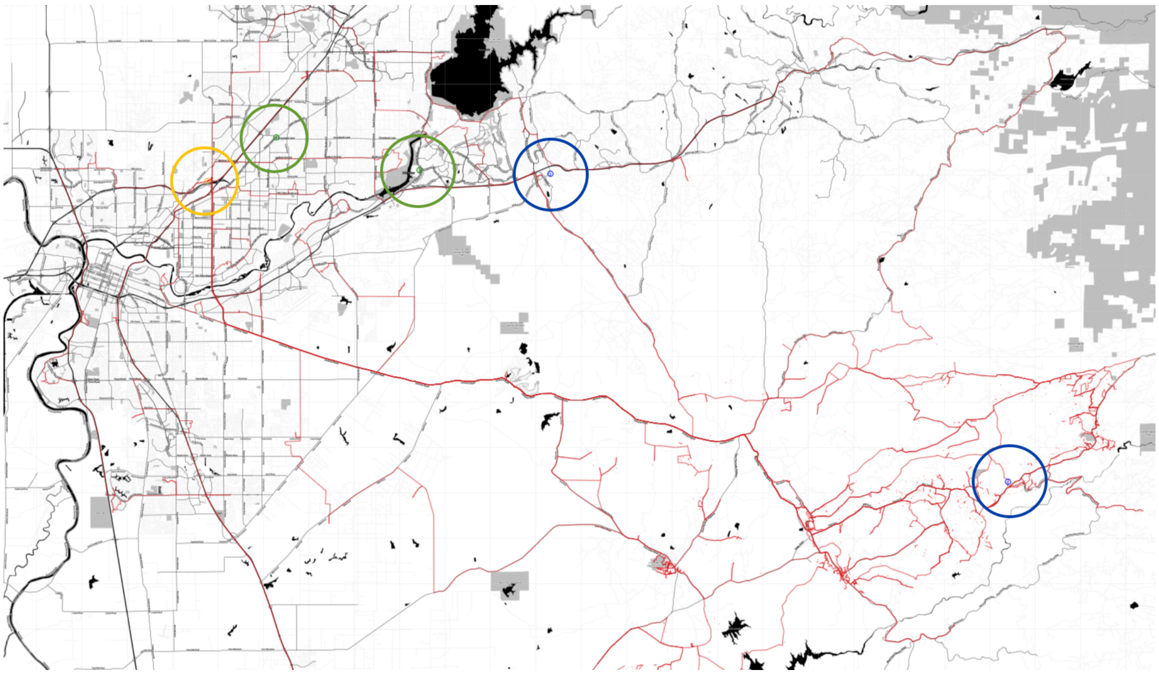


Figure 15: Map of Delivery Van Routes, Central Depot (yellow circle), Two Existing Hydrogen Stations (green circles), and Two Additional Satellite Stations (blue circles)

Figure 16 shows the station utilization of the various stations, with heavier utilization of the satellite stations than the existing stations. This is because the optimization attempts to minimize detouring from the prescribed routes for fueling. However, the second satellite station is not strictly required as the existing stations could be used as in the case with just the one satellite station, just with a somewhat higher level of detour miles for fueling.

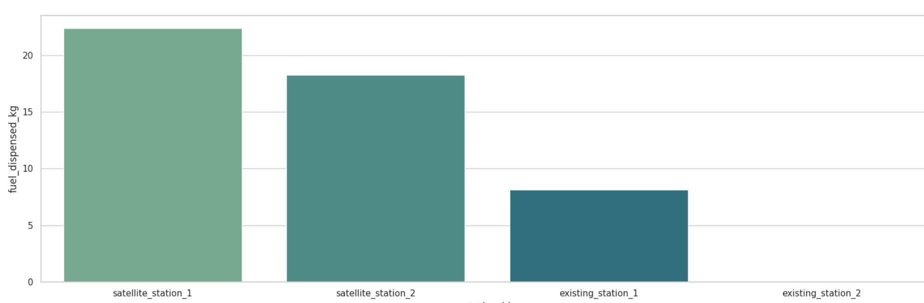


Figure 16: Hydrogen Station Usage for Simulated Delivery Van Routes: 10 kg of Onboard Storage, 2 Existing and 2 Additional Satellite Fueling Stations

Figure 17 shows the fuel level profiles for the 11 delivery vans in this simulation case. Six of the 11 vans take advantage of refueling outside of the central depot location, while 5 of them can complete their routes without additional refueling on an example day. However, 2 of the vans arrive back at the depot essentially empty with fuel, suggesting they would need to refuel under some less favorable conditions such as hot/cold weather (to the extent cabin heating and cooling is employed), road detours, etc.

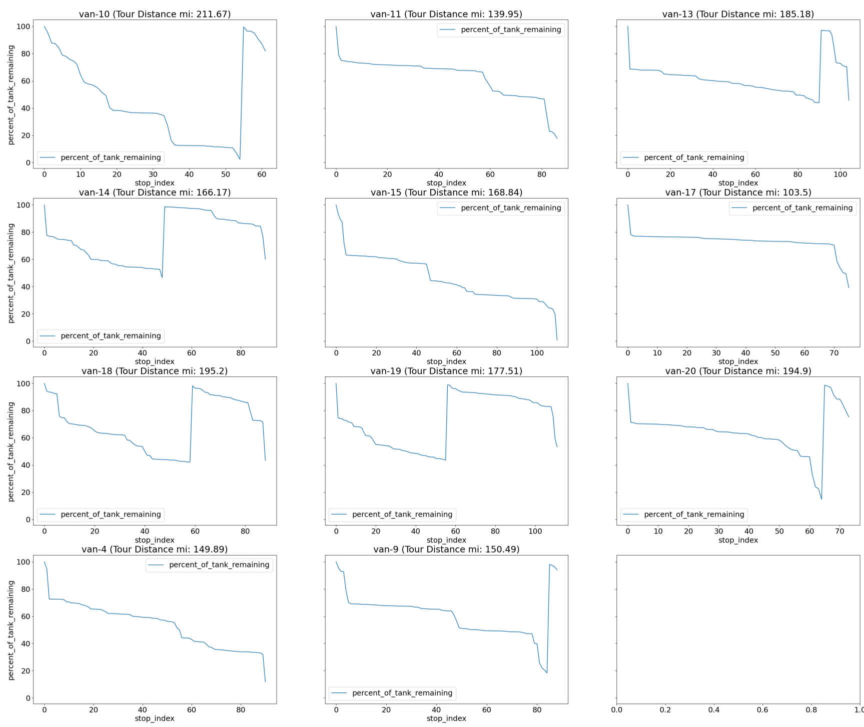


Figure 17: Hydrogen Storage Levels for Simulated Delivery Van Routes: 10 kg of Onboard Storage, 2 Existing and 2 Additional Satellite Fueling Stations

As is to be expected, delivery vans with 7.5 kilograms of hydrogen storage versus 10 kilograms are more reliant on existing and satellite stations to supplement the central depot fueling to complete their routes. As shown in Figure 18, there is considerably more auxiliary refueling in this lower onboard storage case than with the central case of 10 kilograms of onboard storage. There is about 49 kilograms of daily auxiliary hydrogen fueling in the 10-kilogram storage case, versus about 60 kilograms in the 7.5-kilogram storage case, both with 2 existing and 2 satellite stations available.

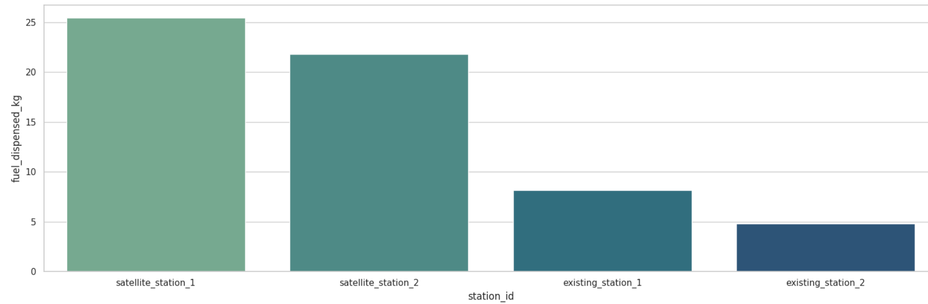


Figure 18: Hydrogen Station Usage for Simulated Delivery Van Routes: 7.5 kg of Onboard Storage, 2 Existing and 2 Additional Satellite Fueling Stations

Meanwhile, if 15 kilograms of hydrogen storage is included on the delivery vans, which we note is somewhat challenging from a "vehicle packaging" perspective for a Class 6 vehicle, there is essentially no need for auxiliary refueling in these simulations (Figure 19). Regardless of the number of satellite stations along with the 2 existing stations, all driving routes for the delivery vans can be completed based on central depot fueling, even those in excess of 200 miles per day. However, we note that as shown in Figure 20, 3 of the delivery vans return to the depot with less than 20% fuel, even with 15 kilograms of onboard storage, suggesting a relatively low margin of "fuel level safety" on these routes. A complete set of these results can be found in Appendix B.

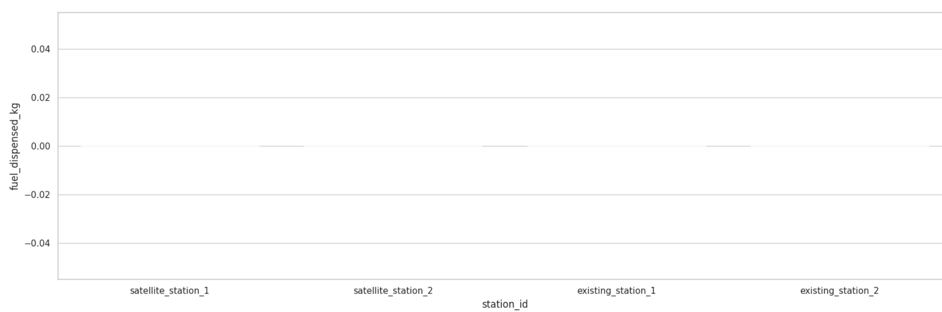


Figure 19: Hydrogen Station Usage for Simulated Delivery Van Routes: 15 kg of Onboard Storage, 2 Existing and 2 Additional Satellite Fueling Stations

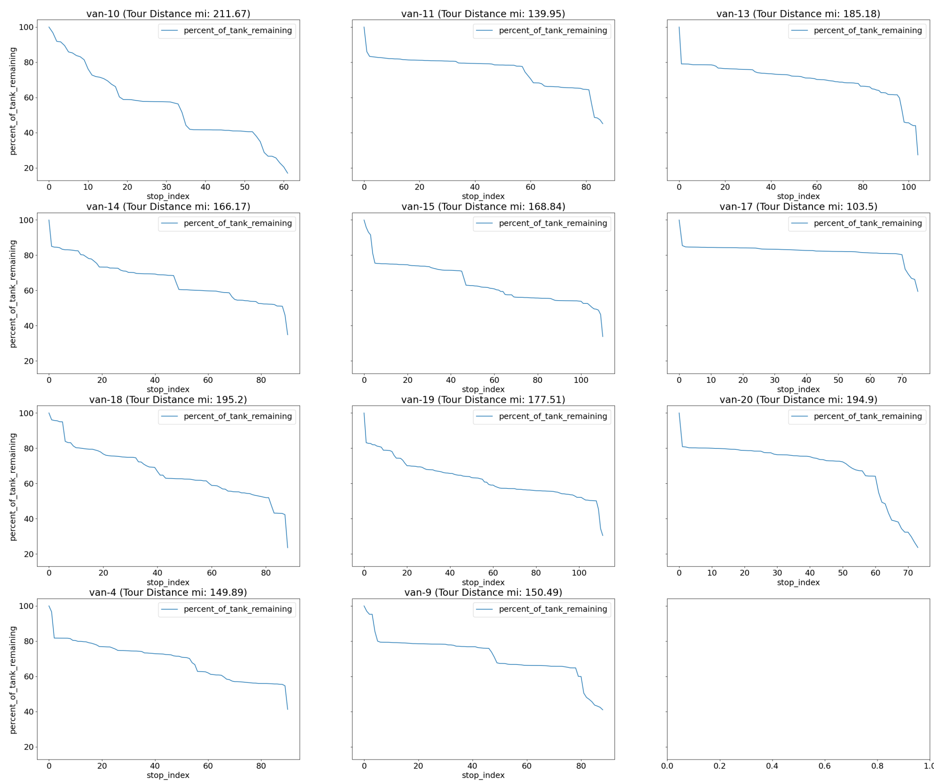


Figure 20: Hydrogen Storage Levels for Simulated Delivery Van Routes: 15 kg of Onboard Storage, 2 Existing and 2 Additional Satellite Fueling Stations

10. Class 8 Hydrogen Fuel Cell Drayage Truck Simulations

With regard to the operation of fuel cell powered Class 8 drayage trucks that would haul cargo containers from seaports and/or airports to warehouse locations for further goods distribution, the project team analyzed a few different potential duty cycles. An urban type driving route is shown in Figure 21, below, and a highway type driving cycle with higher average speeds and less stop and go driving is shown in Figure 22.

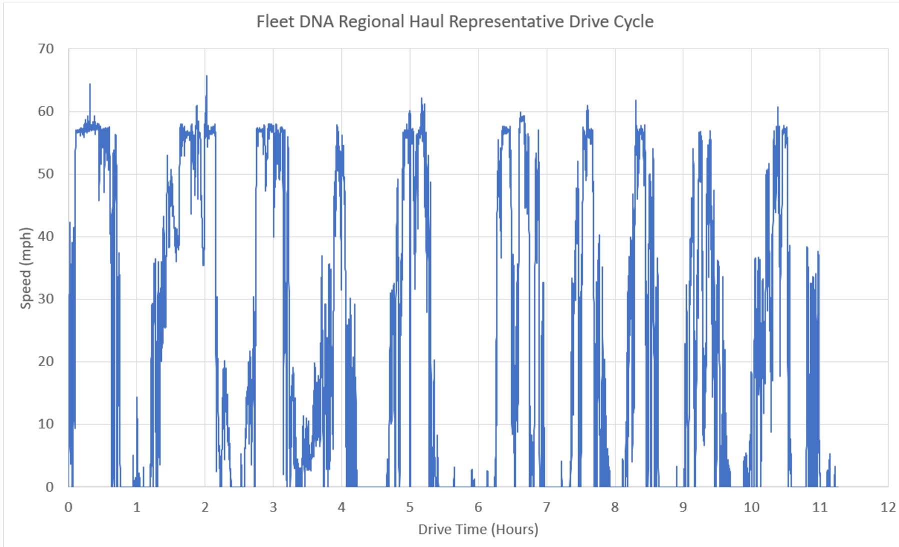


Figure 21: Class 8 Drayage Truck Example Urban Drive Cycle

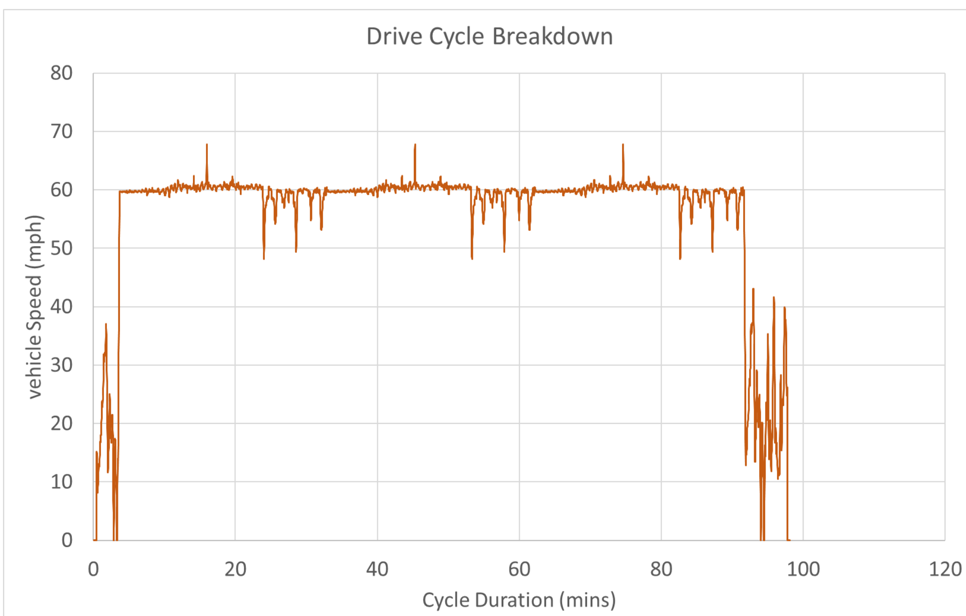
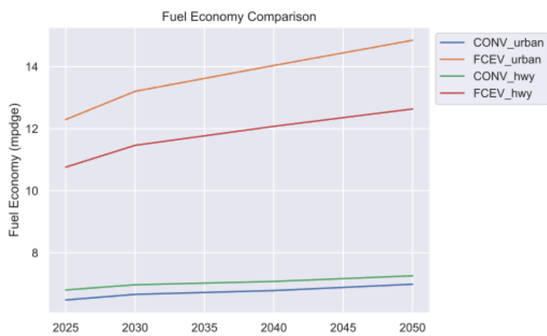


Figure 22: Class 8 Drayage Truck Example Highway Drive Cycle

As shown in Figure 23, the fuel cell trucks have near term fuel economy estimates of about 11 miles per diesel gallon equivalent (mpdge) on the highway cycle and about 12.5 miles per mpdge on the urban cycle, rising slowly to about 12.5 mpdge (highway) and 15 mpdge (urban) by 2050. The total cost of ownership (TCO) is a measure that includes fixed (vehicle capital) costs as well as variable costs for fuel and maintenance. As shown in the figure, the TCO of the fuel cell trucks is considerably higher (on the order of 50%) than the conventional diesel trucks in the 2025-2030 timeframe but drops rapidly during that period. By 2040, the TCO is estimated to be lower than the conventional vehicles for the urban drive cycle operation, and at parity for the highway drive cycle. By 2045 the TCO of the fuel cell trucks is projected to be lower than the TCO of the conventional vehicles for both drive cycles.



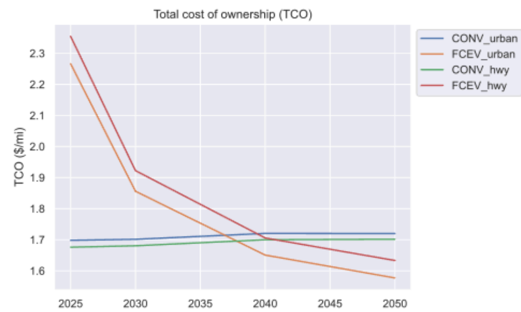
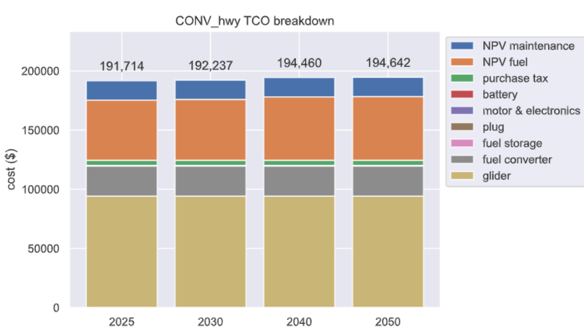


Figure 23: Conventional and Fuel Cell Class 8 Drayage Truck Fuel Economy and TCO Estimates

A detailed breakdown of these TCO estimates is shown in Figures 24 and 25, below, for the vehicles modeled on the highway drive cycle, and in Figures 26 and 27 for the urban drive cycle. The TCO estimates for the conventional diesel trucks are similar in the two cases, while the TCO estimates for the fuel cell trucks are slightly lower in the urban drive cycle case. And once again, the TCO of the fuel cell trucks is higher than the conventional vehicles through about 2040, after which it drops below the conventional truck TCO.



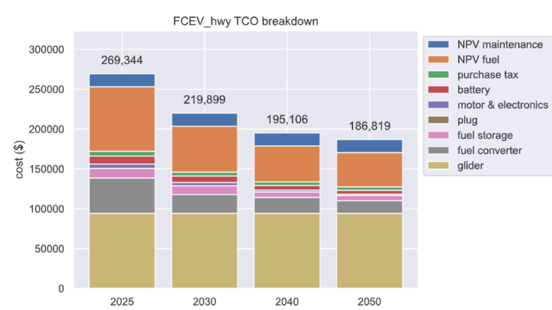


Figure 24: Conventional and Fuel Cell Class 8 Drayage Truck TCO – Highway Cycle

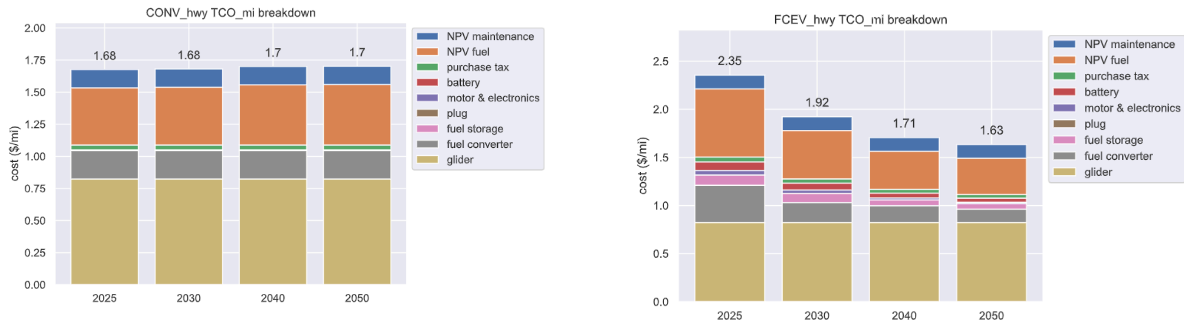


Figure 25: Conventional and Fuel Cell Class 8 Drayage Truck TCO Per Mile – Highway Cycle

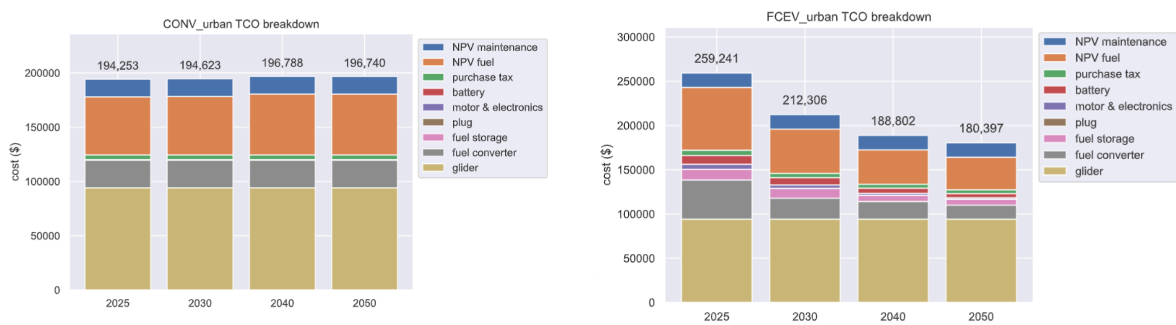


Figure 26: Conventional and Fuel Cell Class 8 Drayage Truck TCO – Urban Cycle

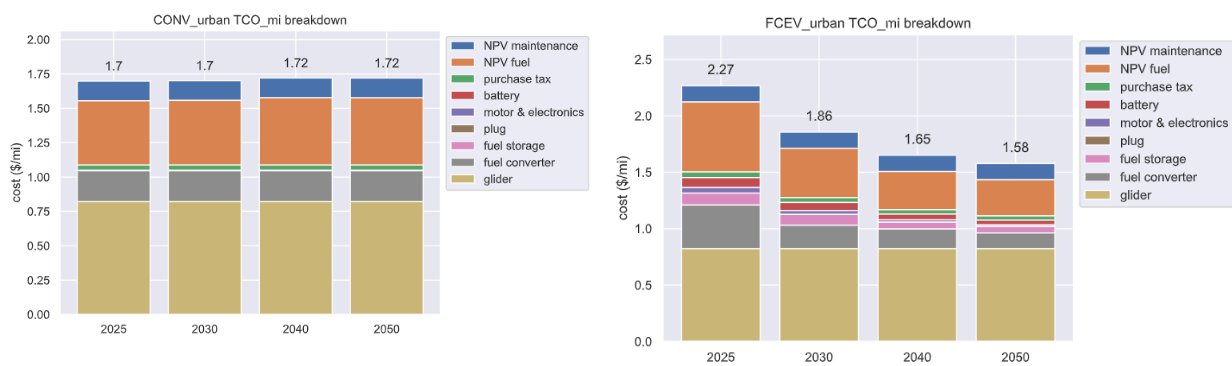


Figure 27: Conventional and Fuel Cell Class 8 Drayage Truck TCO Per Mile – Urban Cycle

11. Impacts of Vehicle Automation for Class 6 Delivery Trucks

Vehicle automation is receiving heavy investments by automakers and other companies for potential benefits including operational efficiencies. Automating vehicles can be done at different levels, from basic driver assist features such as lane keeping and adaptive cruise control, to full automation where no driver is needed for the vehicle. For goods delivery vehicles, where human drivers will likely always be needed for most settings to provide reliable package delivery, automation could provide "ecodriving" benefits by reducing fuel use due to more optimal driving dynamics including gentler accelerations, better use of regenerative braking (for electric drive vehicles), and adherence to speed limits. Automation is most easily integrated into electric drivelines, with much simpler controls and powertrains than conventional combustion vehicles.

The project team consulted with experts at the University of California on the costs and benefits of automation for Class 6 goods delivery vans operating on fuel cell systems. Based on research conducted at UC Berkeley and UC San Diego, a fuel economy improvement of 10% was assumed for purposes of this study, for the types of urban/semi-rural routes modeled here (SAE, 2019). As shown in Table A-1 (Appendix A), this fuel economy benefit comes at the expense of 1 kW in additional electrical "road load" due to the computers and sensors needed for automation, slightly eroding the estimated 10% fuel economy benefit.

Figure 28 presents the TCO findings, where the net impact of automation is a reduction in TCO that translates to a per-mile cost reduction of about \$0.05, or an overall lifetime TCO reduction of about \$5,000 relative to the non-automated fuel cell vehicles with the various hydrogen storage capacities.

Figure 28: Class 6 Delivery Van TCO Impact of Vehicle Automation

12. Key Project Findings and Conclusions

Direct goods delivery to households and businesses is a growing industry, including major corporations such as UPS, FedEx, Amazon, DHL, and many others around the U.S. and the world. Along with other transportation sectors, goods delivery from ports and airports to distribution centers, to then final delivery to customers, will be under pressure to reduce harmful emissions and the use of fossil fuels. Hydrogen FCVs along with battery EVs and very low-carbon biofuels are the leading options, with each having advantages under different duty-cycle conditions, for different classes of vehicles, and for different regions/topographies.

Modeling goods delivery routes and the end-use box truck operations, as well as the further upstream delivery of large, containerized freight through larger Class 8 trucks involves various complexities. These include realistic representations of what those detailed networks look like in a geographical sense, representing characteristics of the relevant FCVs and their conventional counterparts, estimating their energy use in operation, and computing initial estimates of vehicle and fuel costs.

This ATLAS project has accomplished the following objectives:

- Developed scenarios and example delivery routes and route optimization using Graphhopper with up to 20 Class 6 delivery vehicles and up to 1,000 discrete delivery stops in a given simulation;
- Analyzed the operation of Class 8 drayage trucks in both highway and urban drive cycle simulations;
- Developed methodology for realistic estimation of MDV/HDV energy use, combining Graphhopper routing information and output json files with NREL FASTSim/T3CO modeling capabilities;
- Conducted hydrogen station economic and dispensed fueling cost analysis;
- Conducted in-depth analysis of Sacramento/Amado, California region with 11 delivery routes, 1,000 delivery locations, and various depot and auxiliary station configurations; and
- Examined the potential impacts of vehicle automation on the operational efficiency of the Class 6 delivery trucks.

Important findings from the project include:

- Fuel cell powered Class 6 delivery vans become cost competitive on a TCO basis with conventional delivery vans after 2030 in these simulated delivery networks;
- Class 8 fuel cell-powered drayage trucks become cost competitive with diesel trucks on a TCO basis after 2035 in both highway and urban drive cycle simulations;
- Supplemental fueling to extend depot-based fueling from existing and new satellite stations is important for 7.5kg H2 storage delivery vans in semi-rural networks;
- With either 1 or 2 satellite stations and 7.5kg of H2 storage, fuel levels get very low on the longer duty cycle range vehicles by end of shift, suggesting the need for significant levels of auxiliary fueling and somewhat broader station coverage;
- Supplemental fueling from existing and new satellite stations is still important for 10kg H2 storage delivery vans in semi-rural networks, where some routes cannot be completed based on central depot fueling only;

- Supplemental fueling from existing and new satellite stations is not needed for 15kg H2 storage delivery vans in the semi-rural networks simulated here; and
- Vehicle automation for Class 6 delivery vans is estimated to provide a 10% reduction in fuel use for a per-mile cost reduction of about $0.05, or an overall lifetime TCO reduction of about $5,000 relative to the non-automated fuel cell vehicles with the various hydrogen storage capacities.

In conclusion, we find that fuel cell technologies may have limited applications in dense urban areas delivery van operation, where driving distances tend to be under 150 miles per day and where battery-based technologies may offer sufficient performance. However, in suburban and semi-rural routes, where delivery vans have duty cycles of over 200 miles per day in some cases, hydrogen fuel cell vehicles may be the best option in the future especially when TCO become competitive or even less than those of conventional vehicles.

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Appendix A – ATLAS Project Simulation Matrix

Table A-1: Key Vehicle and Specifications and ATLAS Scenarios

Case	Fuel Cell Power (W/kg)	Fuel Cell System Peak Effic. (%)	Fuel Cell Cost ($/kW)	H2 storage fixed cost	H2 storage variable cost ($/kg)	Aux. Battery Cost ($/kW) ANL hybrid high	Class 6 vehicle H2 storage (kg)
1 – 2025	700	65%	$126	$3,366	$274	$20	10 kg
1 – 2030	800	67%	$70	$3,029	$247	$18.5	10 kg
1A – 2030 w/Automation (1 kW extra road load +10% FE increase)	800	67%	$70	$3,029	$247	$18.5	10 kg
1 – 2040	900	69%	$60	$2,861	$233	$17.6	10 kg
1 – 2050	1000	70%	$50	$2,693	$219	$17.3	10 kg
2 – 2025	700	65%	$126	$3,366	$274	$20	7.5 kg
2 – 2030	800	67%	$70	$3,029	$247	$18.5	7.5 kg
2A – 2030 (1 kW extra road load +10% FE increase)	*800*	*67%*	*$70*	*$3,029*	*$247*	*$18.5*	*7.5 kg*
2 – 2040	900	69%	$60	$2,861	$233	$17.6	7.5 kg
2 – 2050	1000	70%	$50	$2,693	$219	$17.3	7.5 kg
3 – 2025	700	65%	$126	$3,366	$274	$20	15 kg
3 – 2030	800	67%	$70	$3,029	$247	$18.5	15 kg
3A – 2030 (1 kW extra road load +10% FE increase)	*800*	*67%*	*$70*	*$3,029*	*$247*	*$18.5*	*15 kg*
3 – 2040	900	69%	$60	$2,861	$233	$17.6	15 kg
3 – 2050	1000	70%	$50	$2,693	$219	$17.3	15 kg

Appendix B – Extended Project Results for Sacramento / Amador County Study Region

Figure B-1: Conventional Class 6 Delivery Van Results

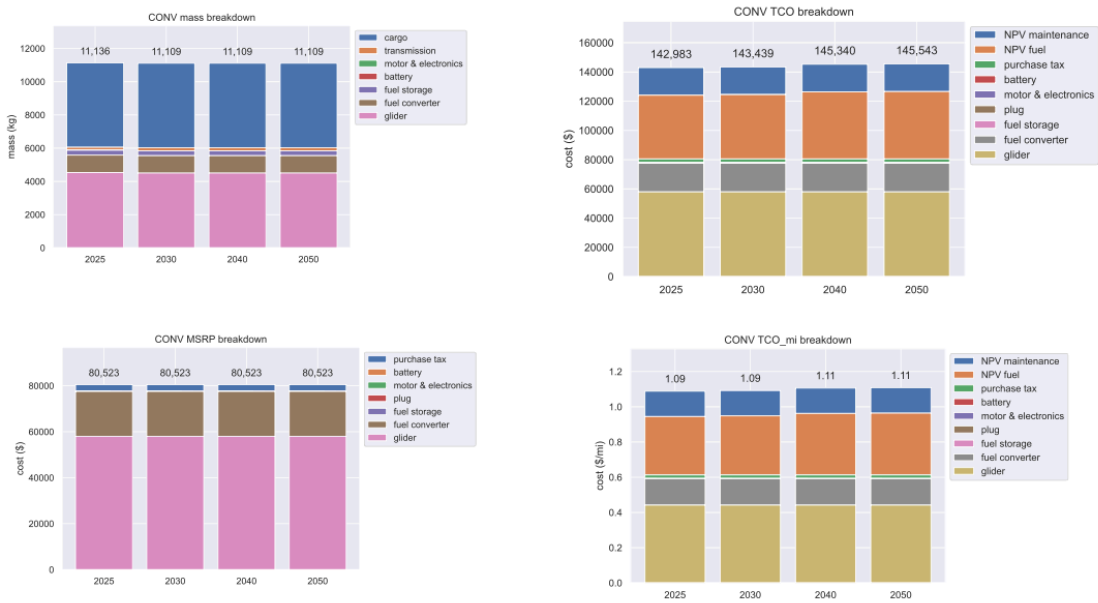


Figure B-2: Fuel Cell Class 6 Delivery Van Results: 10kg Hydrogen Storage

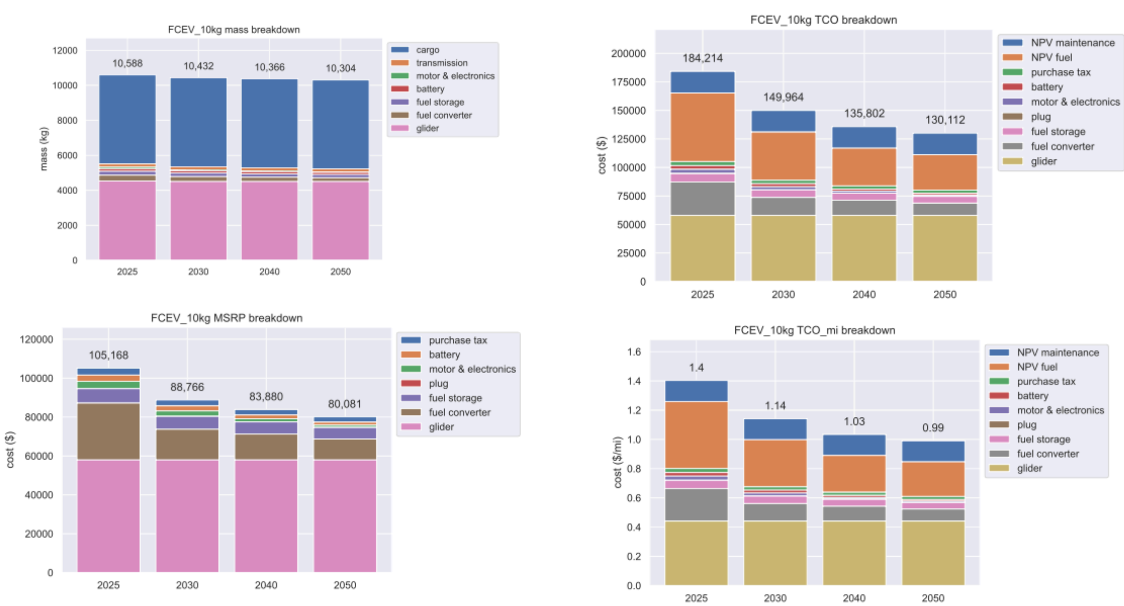


Figure B-3: Fuel Cell Class 6 Delivery Van Results: 7.5kg Hydrogen Storage

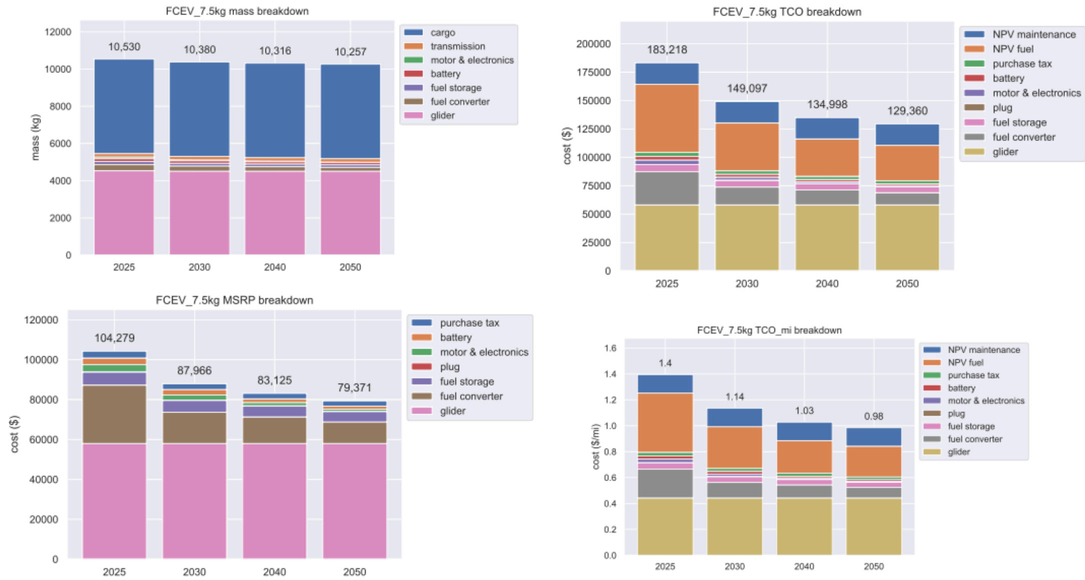


Figure B-4: Fuel Cell Class 6 Delivery Van Results: 15kg Hydrogen Storage

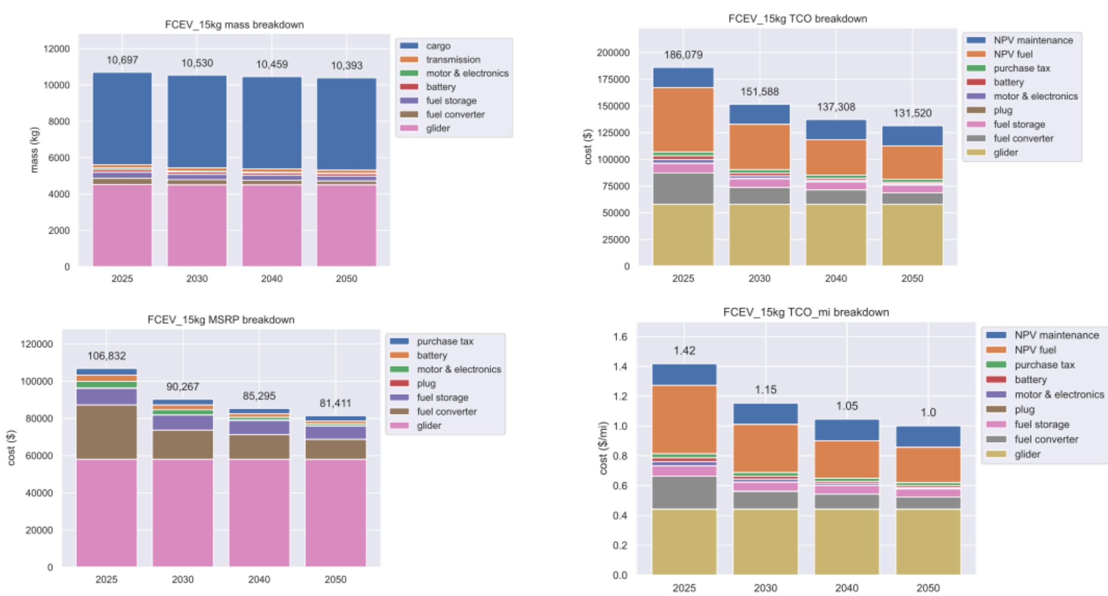


Figure B-5: Class 6 Delivery Van Conventional and Fuel Cell Masses and Cargo Capacity Ratings

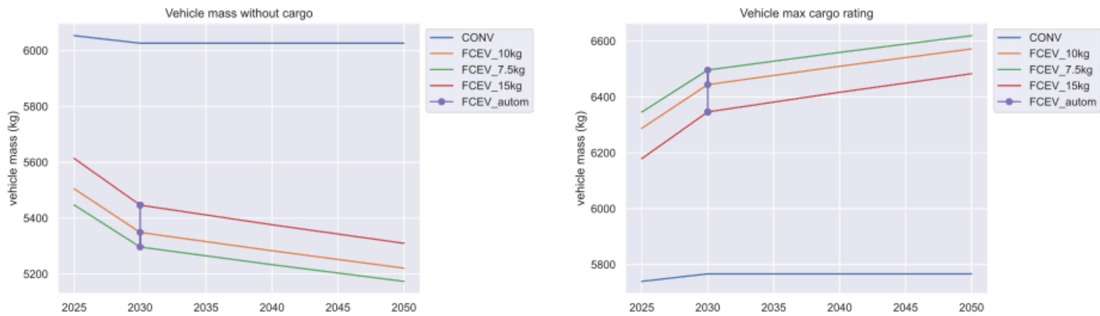


Figure B-6: Conventional and Fuel Cell Class 6 Delivery Van MSRP Estimates

Note: MSRP = manufacturer suggested retail price

Figure B-7: Conventional and Fuel Cell Class 6 Delivery Van TCO Estimates

Note: TCO = total cost of ownership

Figure B-8: Conventional and Fuel Cell Class 8 Drayage Truck Fuel Economy and TCO Estimates

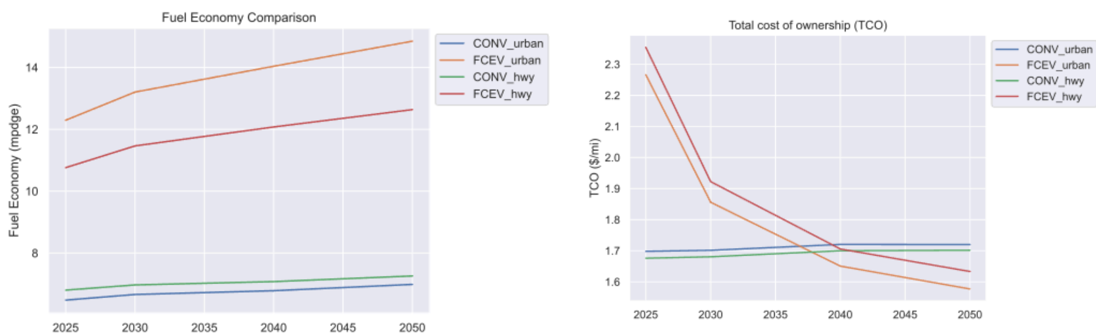


Figure B-9: Conventional and Fuel Cell Class 8 Drayage Truck TCO – Highway Cycle

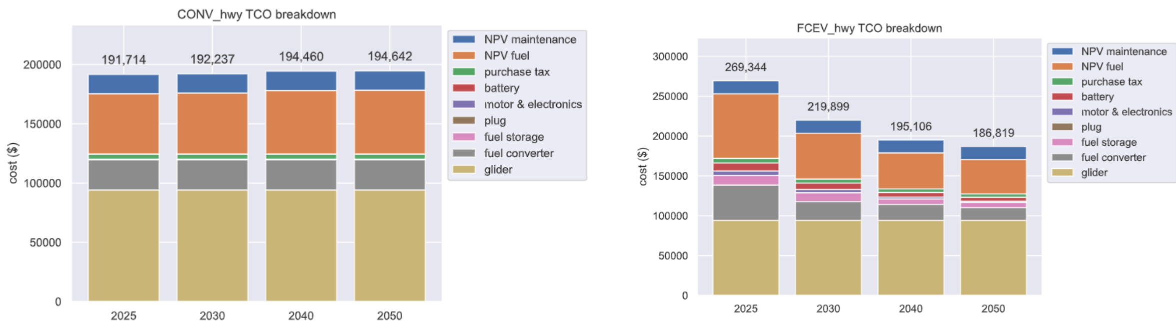


Figure B-10: Conventional and Fuel Cell Class 8 Drayage Truck TCO Per Mile – Highway Cycle

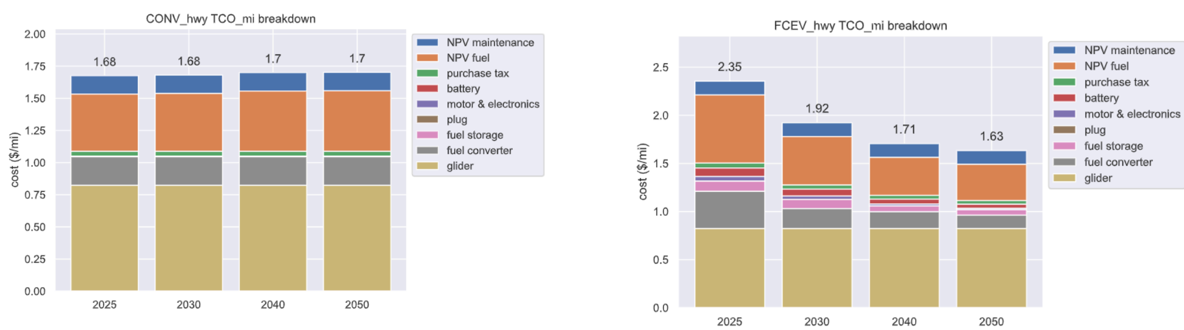


Figure B-11: Conventional and Fuel Cell Class 8 Drayage Truck TCO – Urban Cycle

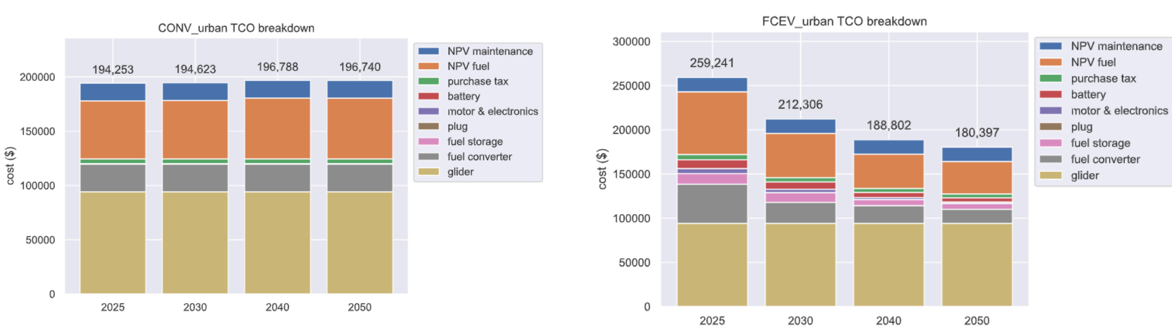


Figure B-11: Conventional and Fuel Cell Class 8 Drayage Truck TCO Per Mile – Urban Cycle

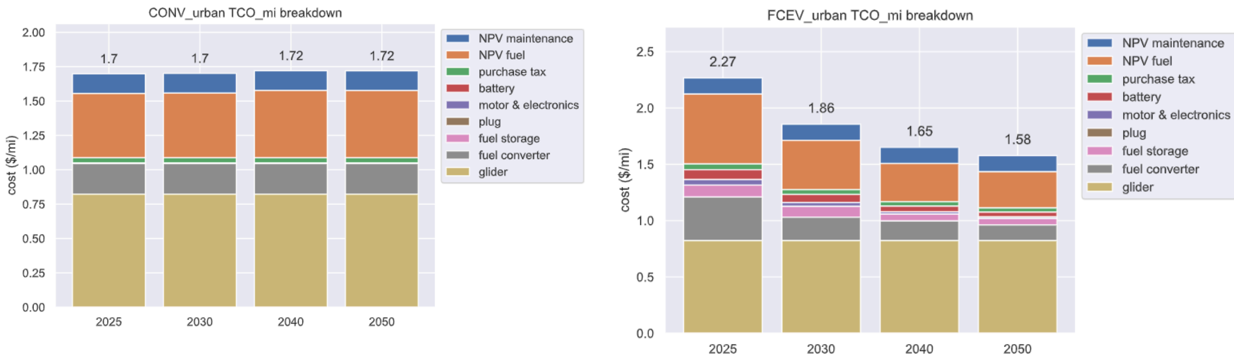


Figure B-12: Hydrogen Station Utilization – 7.5 Kg of Delivery Van Storage and 1 Satellite Station

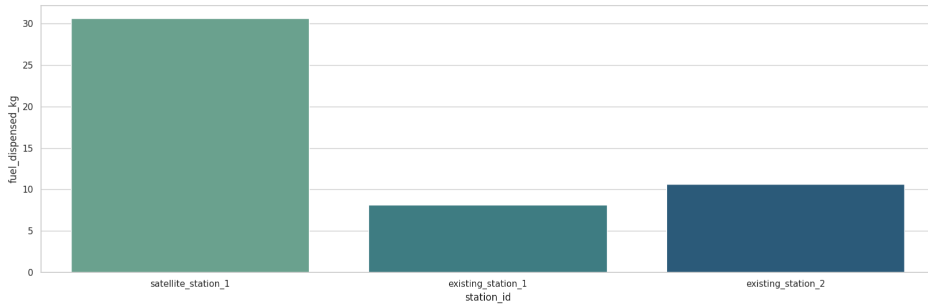


Figure B-13: Vehicle Fuel Use Profiles – 7.5 Kg of Delivery Van Storage and 1 Satellite Station

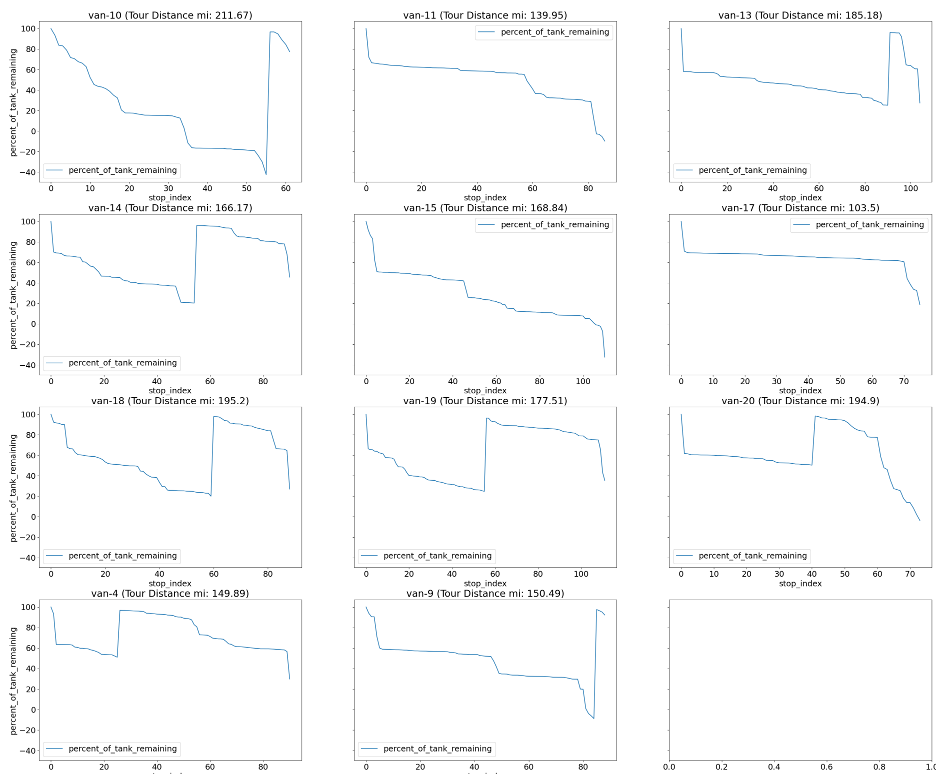


Figure B-14: Hydrogen Station Utilization – 7.5 Kg Delivery Van Storage and 2 Satellite Stations

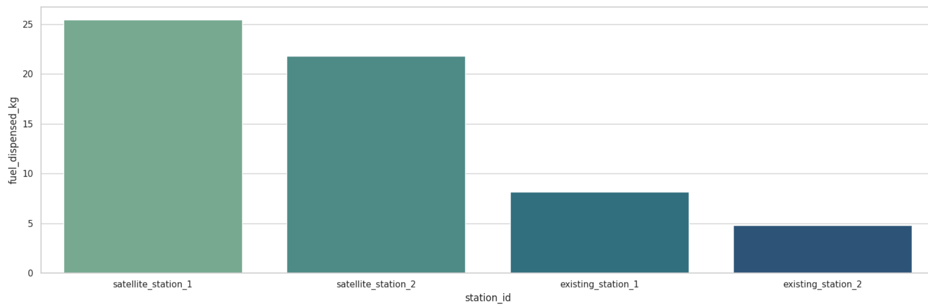


Figure B-15: Vehicle Fuel Use Profiles – 7.5 Kg of Delivery Van Storage and 2 Satellite Stations

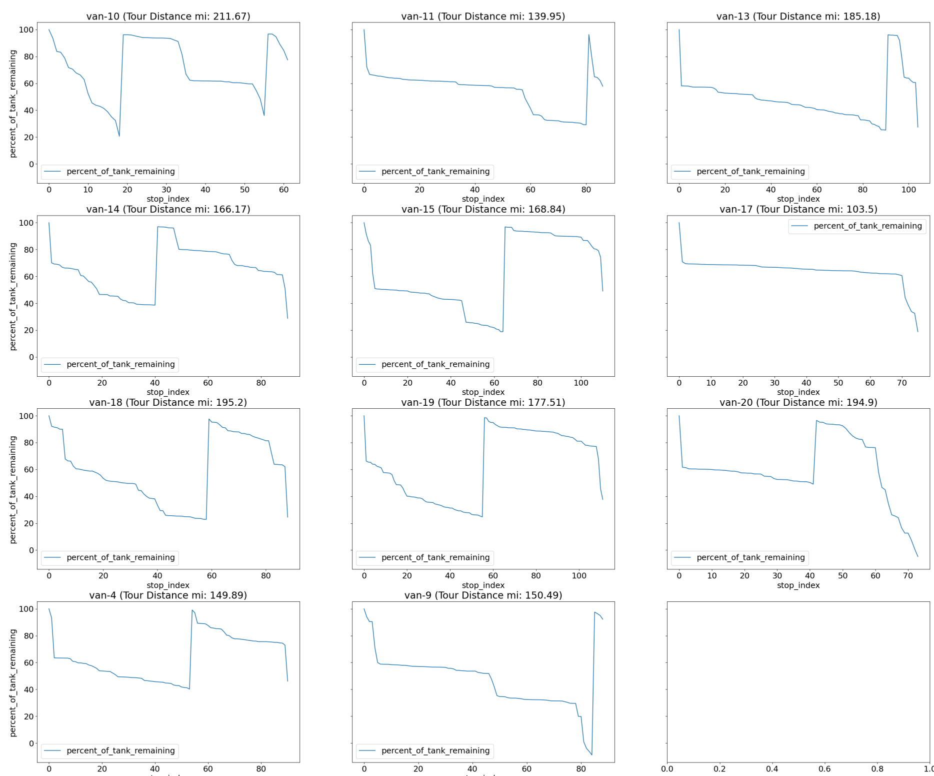


Figure B-16: Hydrogen Station Utilization – 7.5 Kg Delivery Van Storage and 3 Satellite Stations

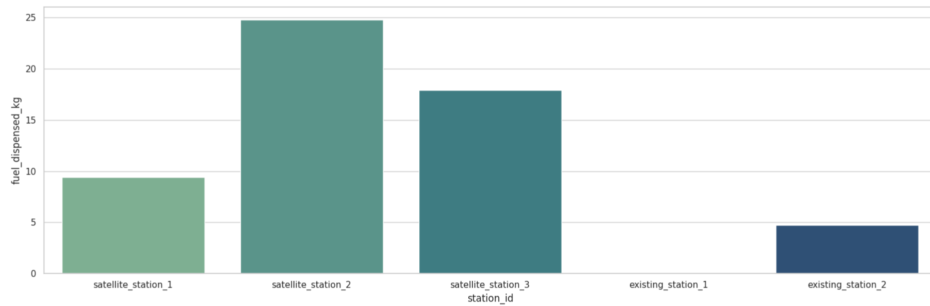


Figure B-17: Vehicle Fuel Use Profiles – 7.5 Kg of Delivery Van Storage and 3 Satellite Stations

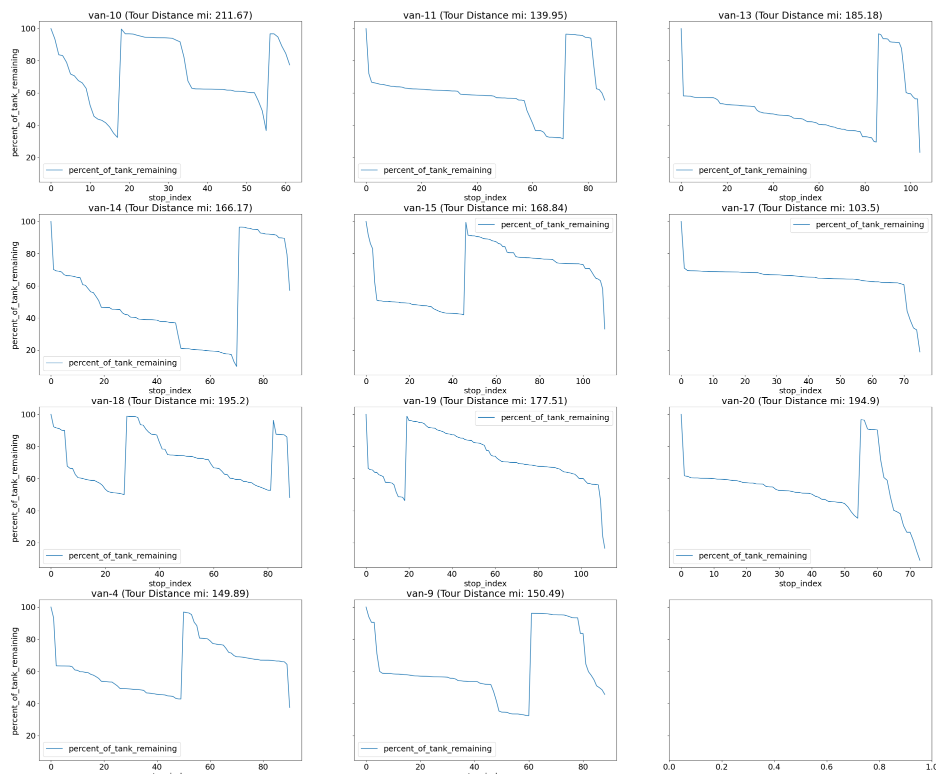


Figure B-18: Hydrogen Station Utilization – 7.5 Kg Delivery Van Storage and 4 Satellite Stations

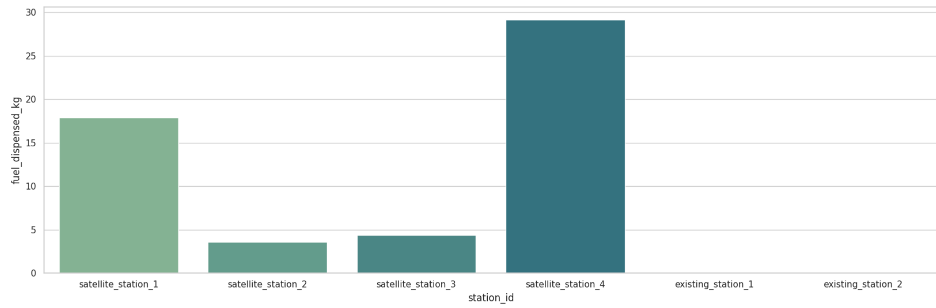


Figure B-19: Vehicle Fuel Use Profiles – 7.5 Kg of Delivery Van Storage and 4 Satellite Stations

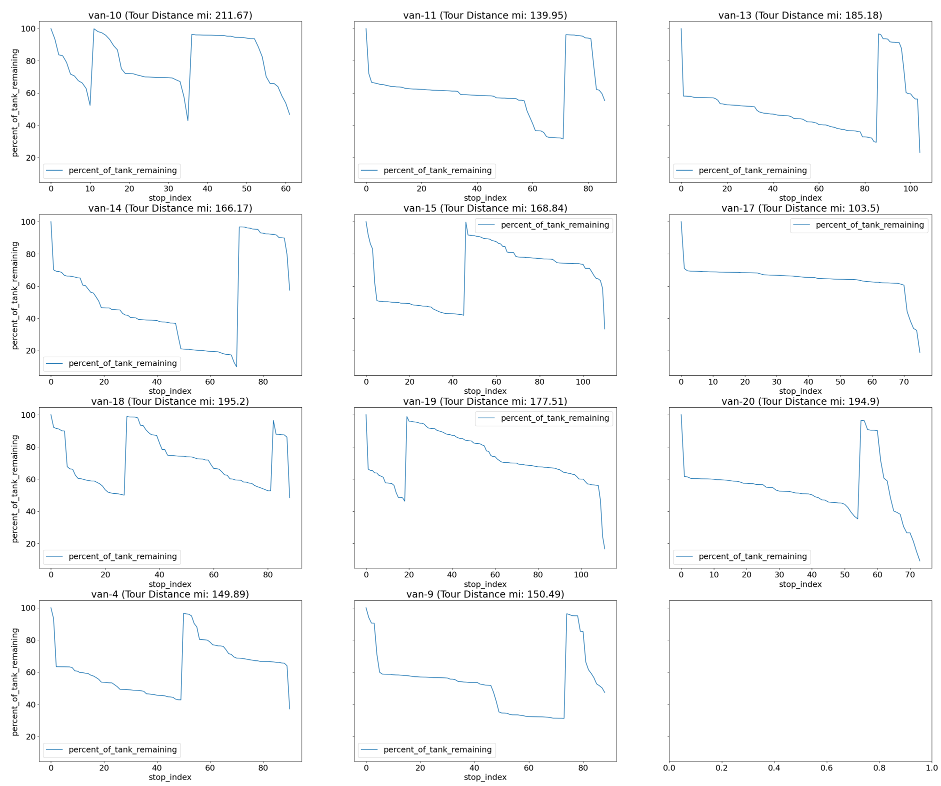


Figure B-20: Hydrogen Station Utilization – 7.5 Kg Delivery Van Storage and 5 Satellite Stations

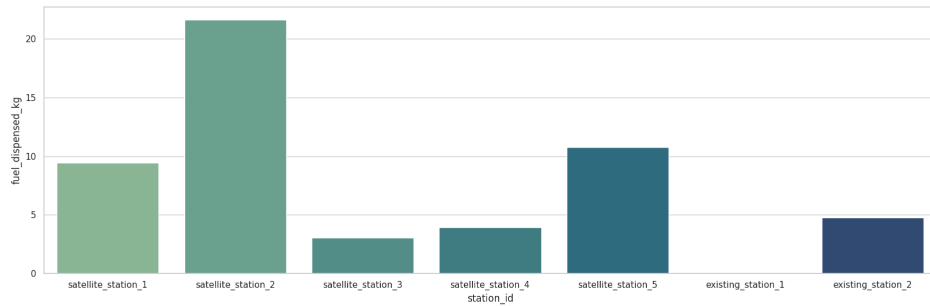


Figure B-21: Vehicle Fuel Use Profiles – 7.5 Kg of Delivery Van Storage and 5 Satellite Stations

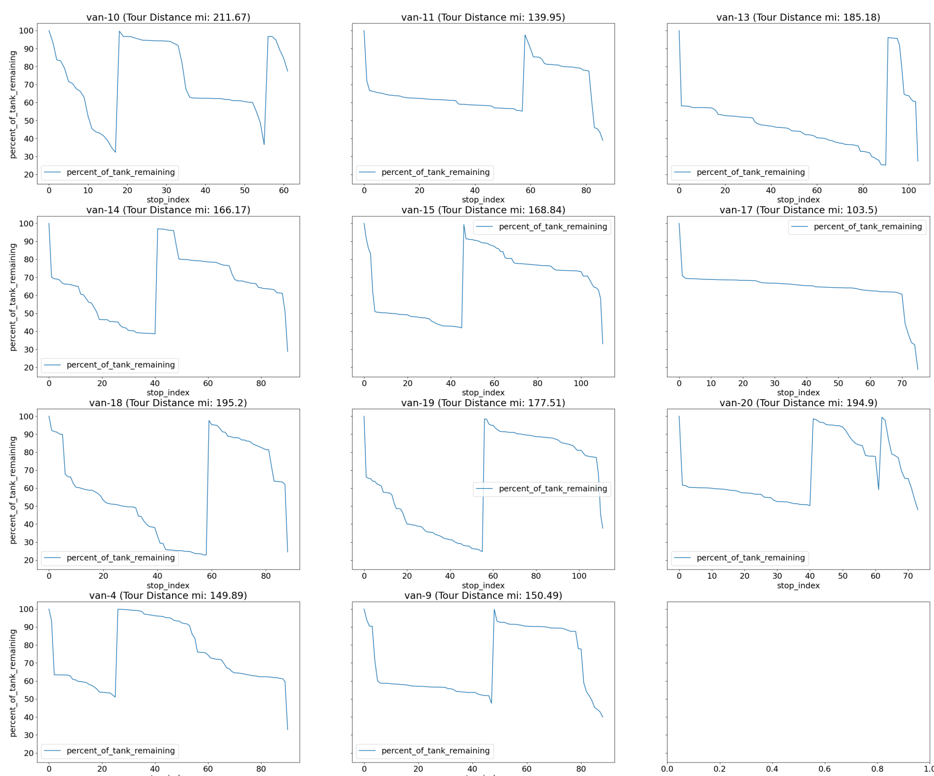


Figure B-22: Hydrogen Station Utilization – 7.5 Kg Delivery Van Storage and 6 Satellite Stations

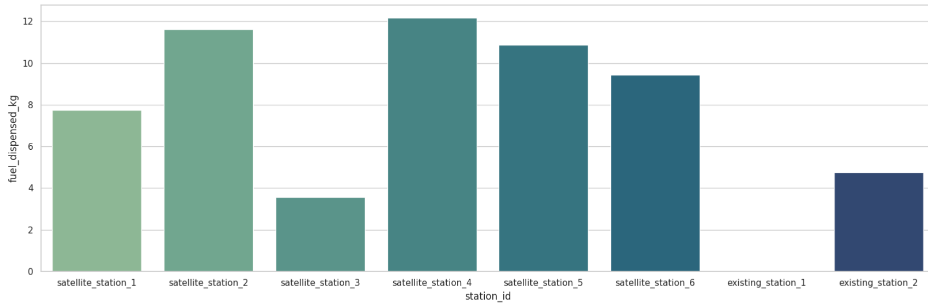


Figure B-23: Vehicle Fuel Use Profiles – 7.5 Kg of Delivery Van Storage and 6 Satellite Stations

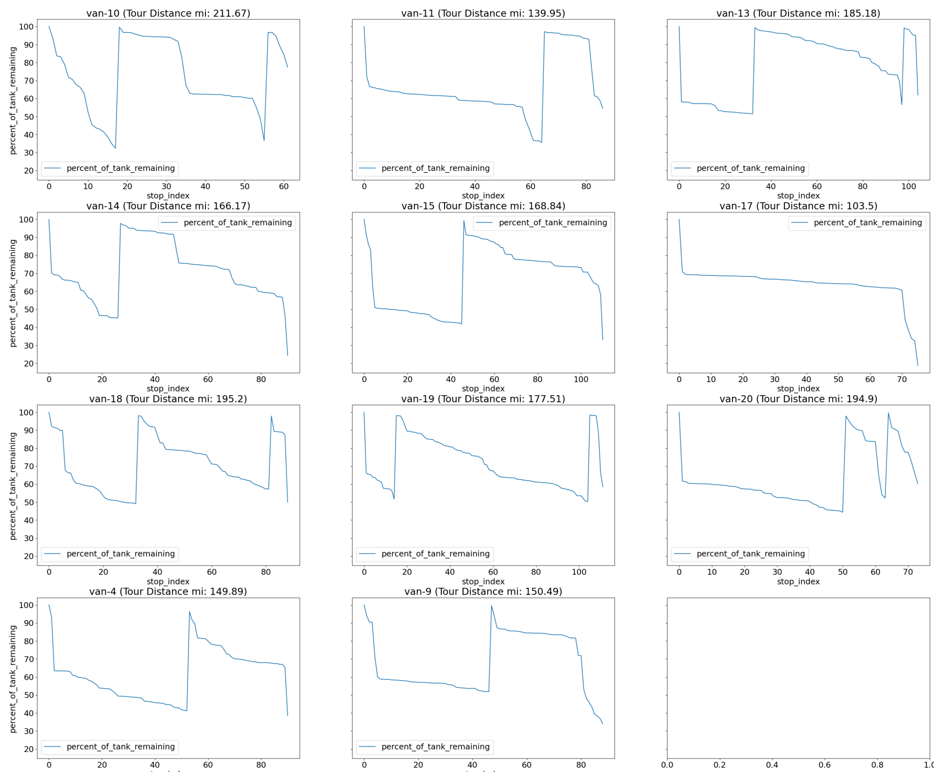


Figure B-24: Hydrogen Station Utilization – 10 Kg Delivery Van Storage and 1 Satellite Station

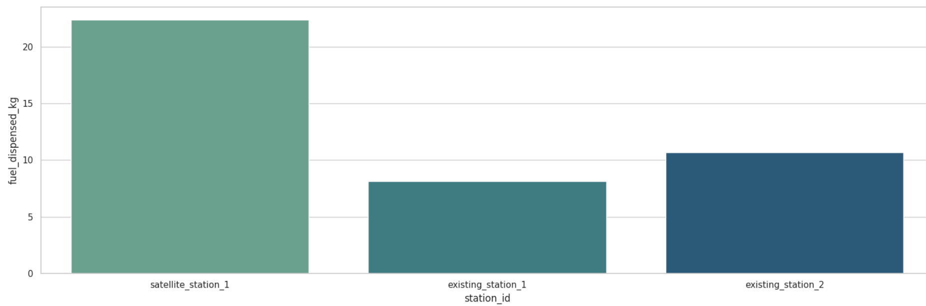


Figure B-25: Vehicle Fuel Use Profiles – 10 Kg of Delivery Van Storage and 1 Satellite Station

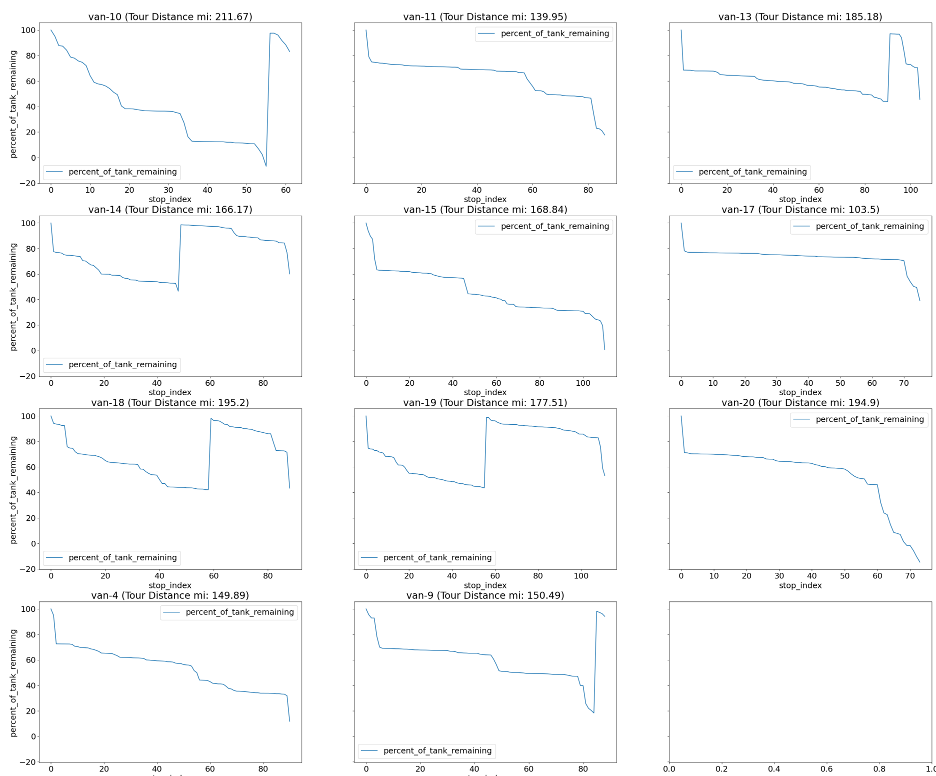


Figure B-26: Hydrogen Station Utilization – 10 Kg Delivery Van Storage and 2 Satellite Stations

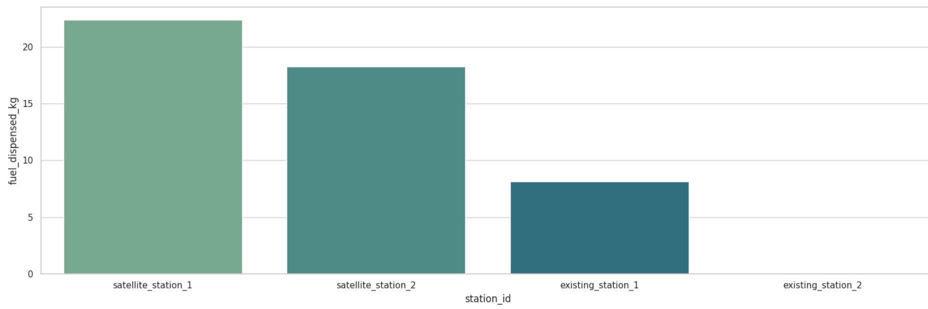


Figure B-27: Vehicle Fuel Use Profiles – 10 Kg of Delivery Van Storage and 2 Satellite Stations

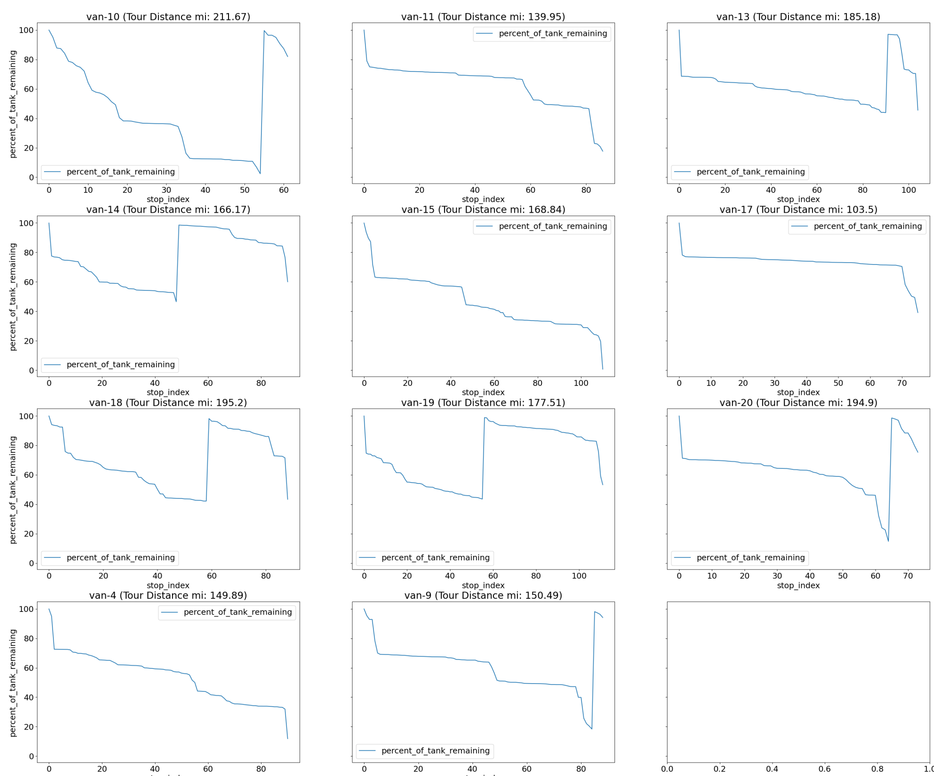


Figure B-28: Hydrogen Station Utilization – 10 Kg Delivery Van Storage and 3 Satellite Stations

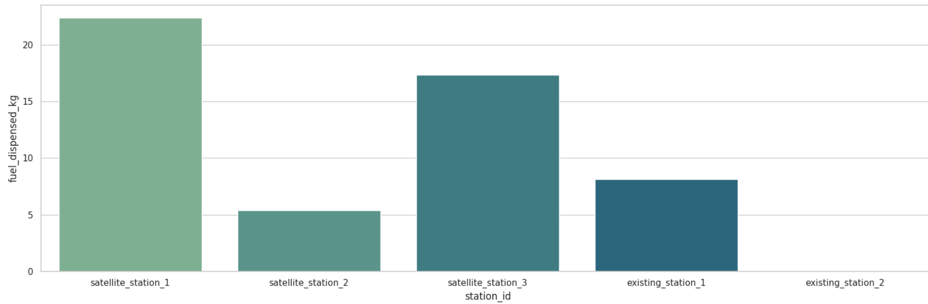


Figure B-29: Vehicle Fuel Use Profiles – 10 Kg of Delivery Van Storage and 3 Satellite Stations

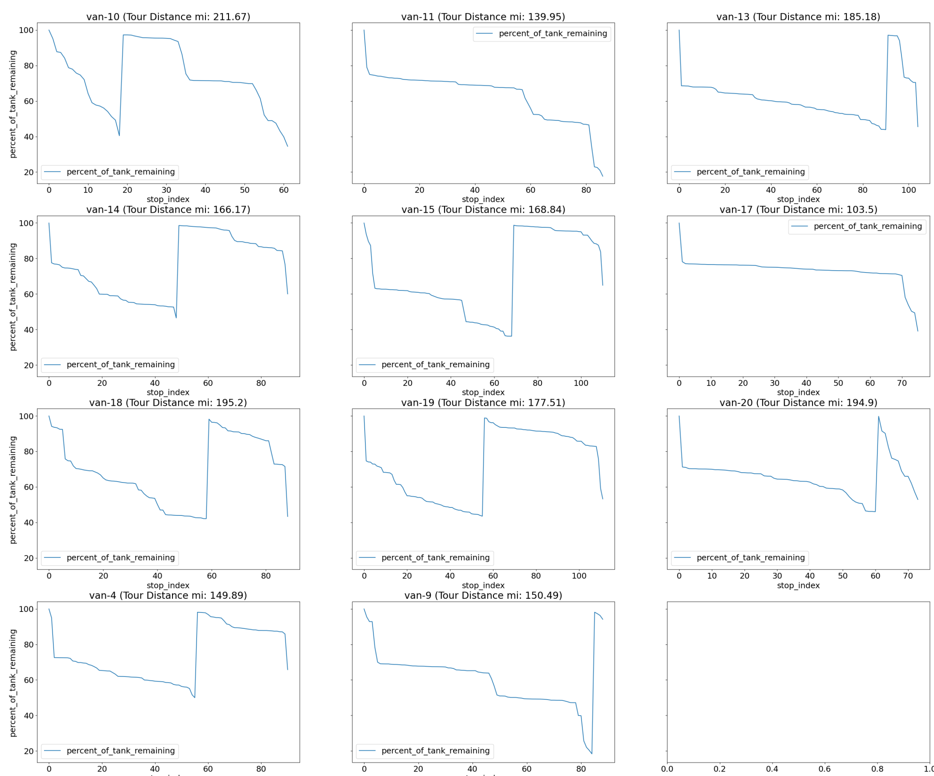


Figure B-30: Hydrogen Station Utilization – 10 Kg Delivery Van Storage and 4 Satellite Stations

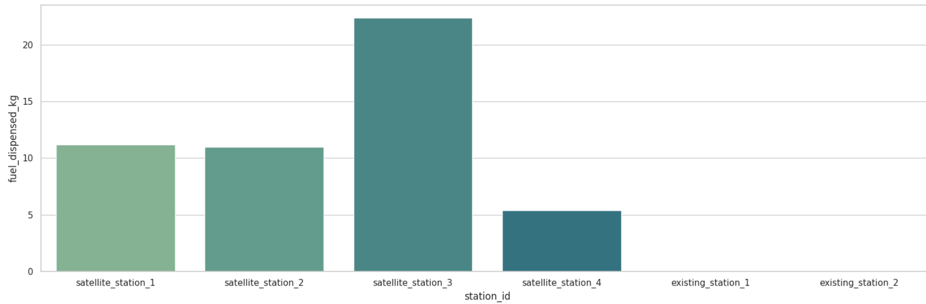


Figure B-31: Vehicle Fuel Use Profiles – 10 Kg of Delivery Van Storage and 4 Satellite Stations

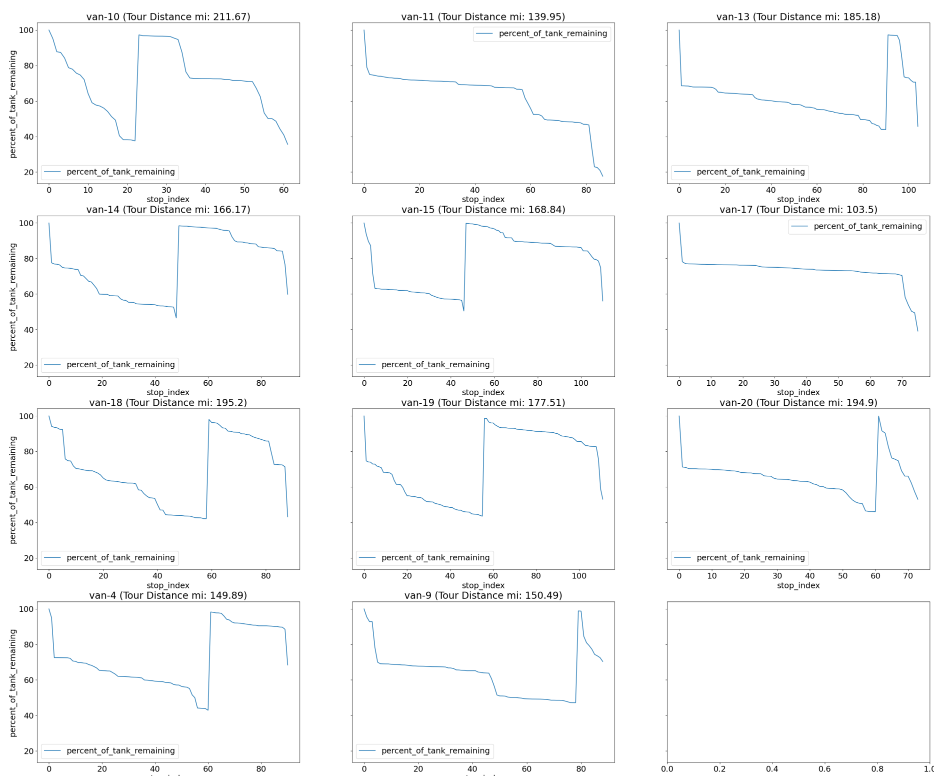


Figure B-32: Hydrogen Station Utilization – 10 Kg Delivery Van Storage and 5 Satellite Stations

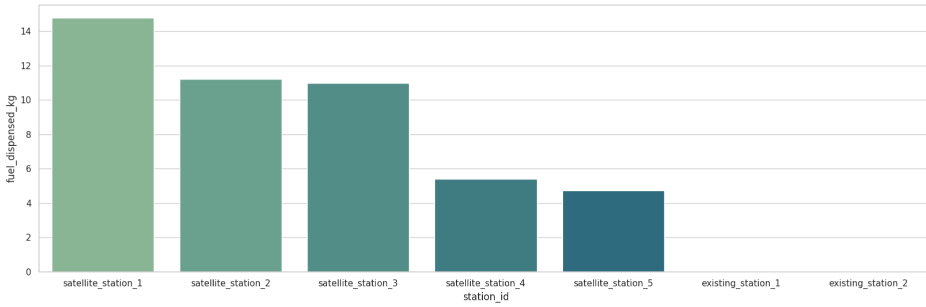


Figure B-33: Vehicle Fuel Use Profiles – 10 Kg of Delivery Van Storage and 5 Satellite Stations

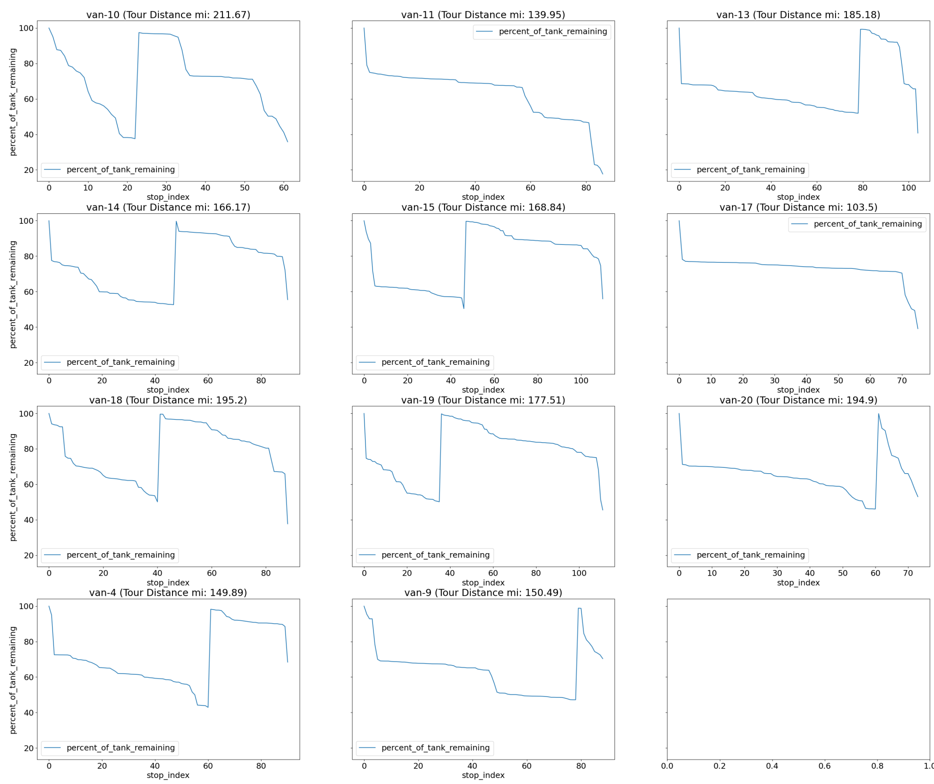


Figure B-34: Hydrogen Station Utilization – 10 Kg Delivery Van Storage and 6 Satellite Stations

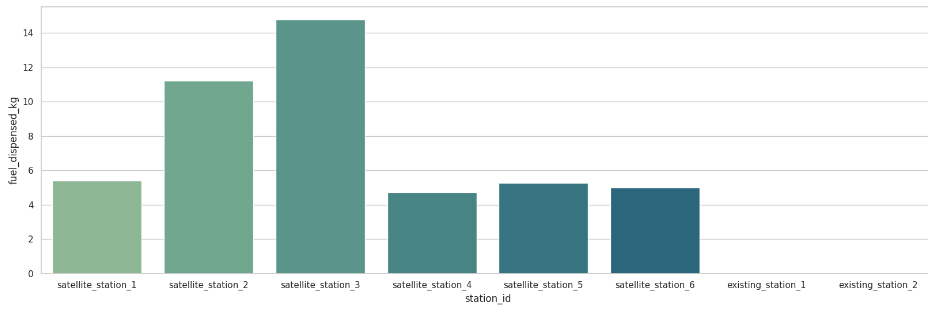


Figure B-35: Vehicle Fuel Use Profiles – 10 Kg of Delivery Van Storage and 6 Satellite Stations

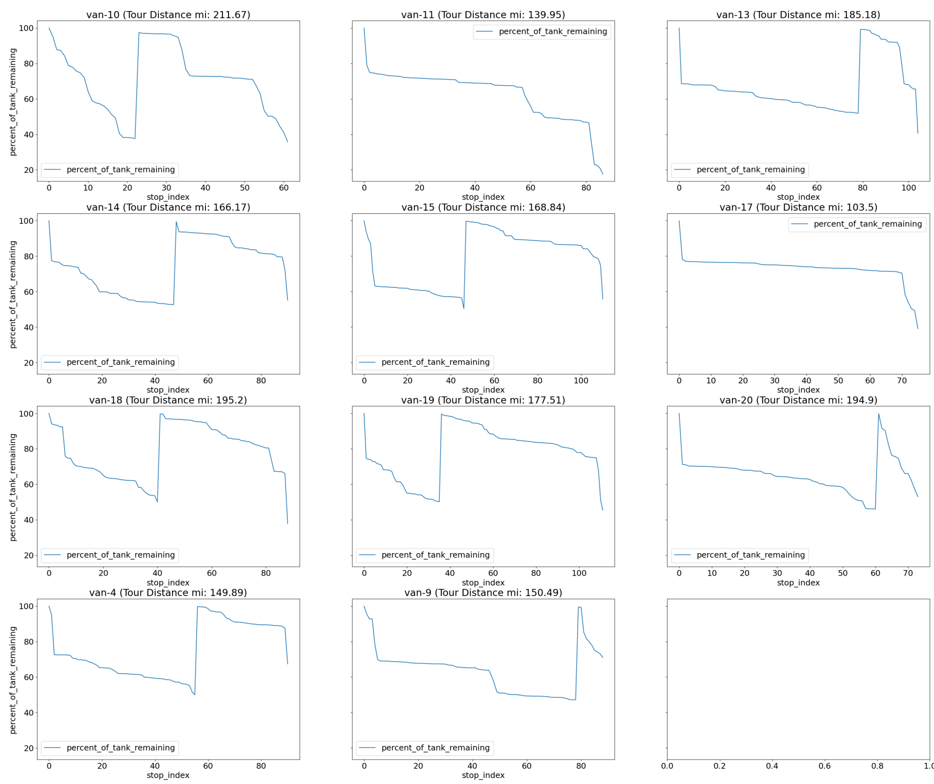
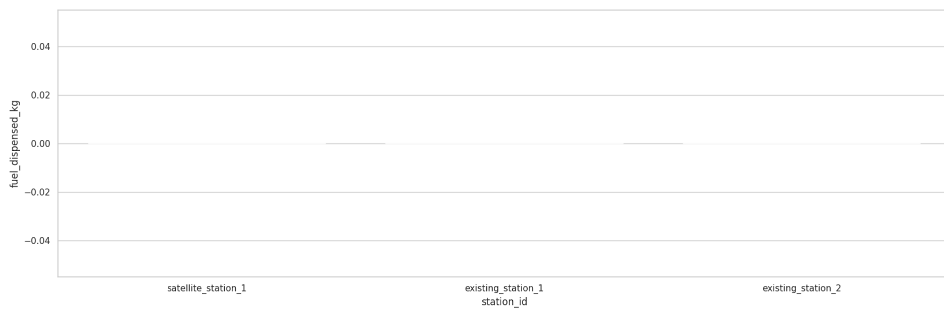


Figure B-36: Hydrogen Station Utilization – 15 Kg Delivery Van Storage and 1 Satellite Station



Note: There is no usage of satellite or existing hydrogen stations with 15 kg of onboard storage

Figure B-37: Vehicle Fuel Use Profiles – 15 Kg of Delivery Van Storage and 1 Satellite Station

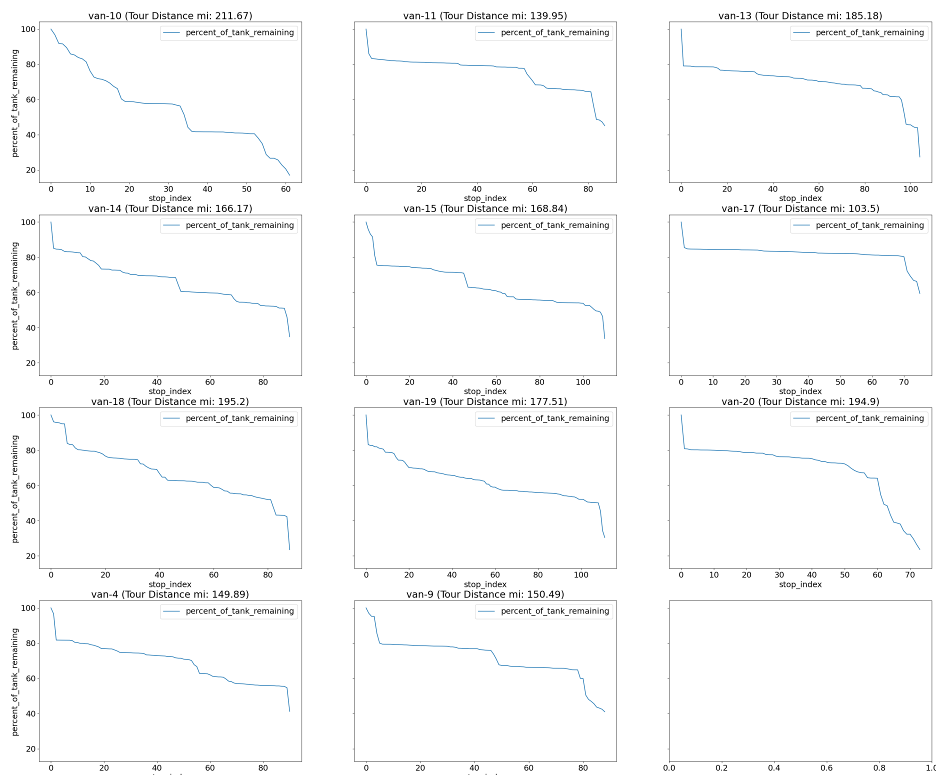
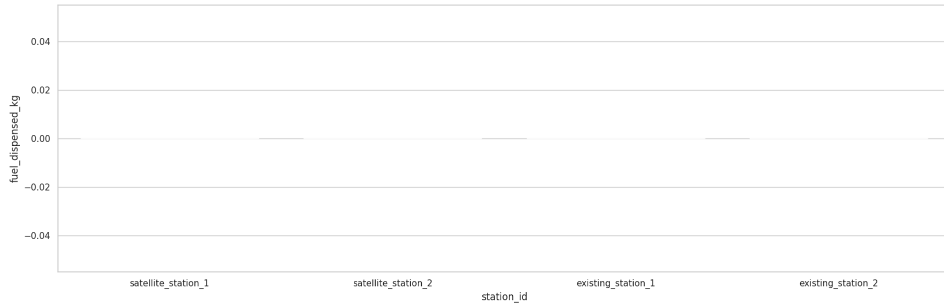


Figure B-38: Hydrogen Station Utilization – 15 Kg Delivery Van Storage and 2 Satellite Stations



Note: There is no usage of satellite or existing hydrogen stations with 15 kg of onboard storage

Figure B-39: Vehicle Fuel Use Profiles – 15 Kg of Delivery Van Storage and 2 Satellite Stations

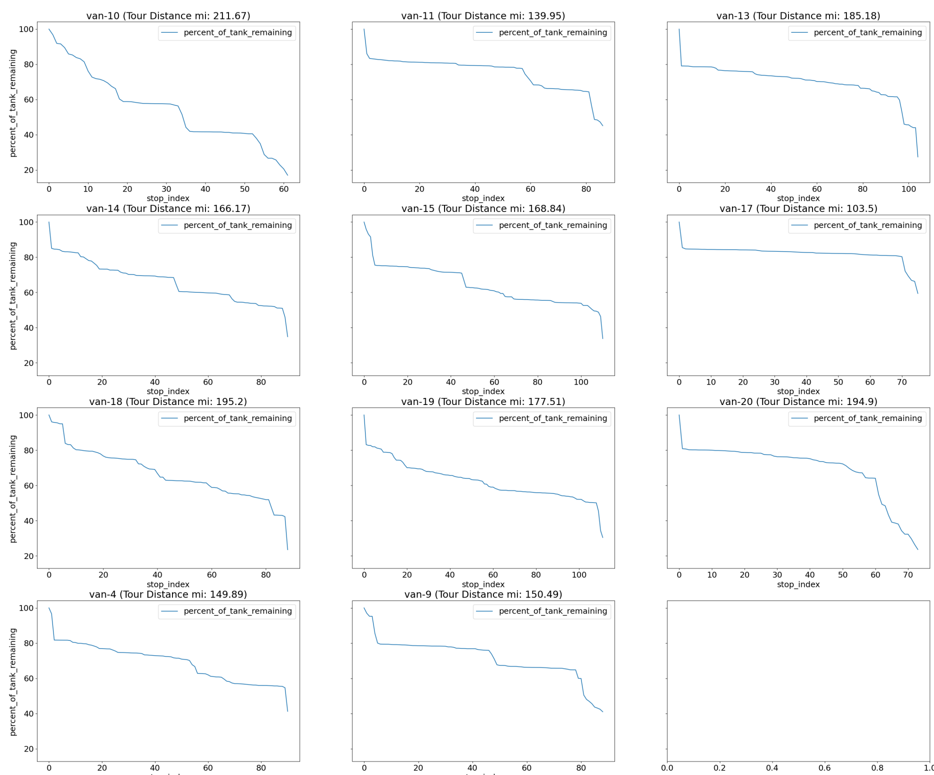
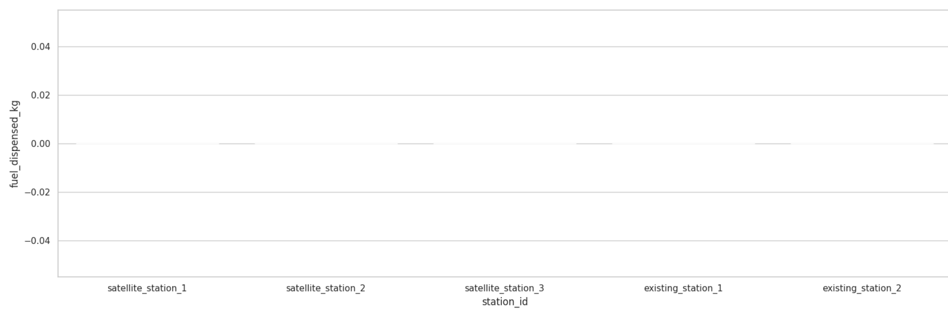


Figure B-40: Hydrogen Station Utilization – 15 Kg Delivery Van Storage and 3 Satellite Stations



Note: There is no usage of satellite or existing hydrogen stations with 15 kg of onboard storage

Figure B-41: Vehicle Fuel Use Profiles – 15 Kg of Delivery Van Storage and 3 Satellite Stations

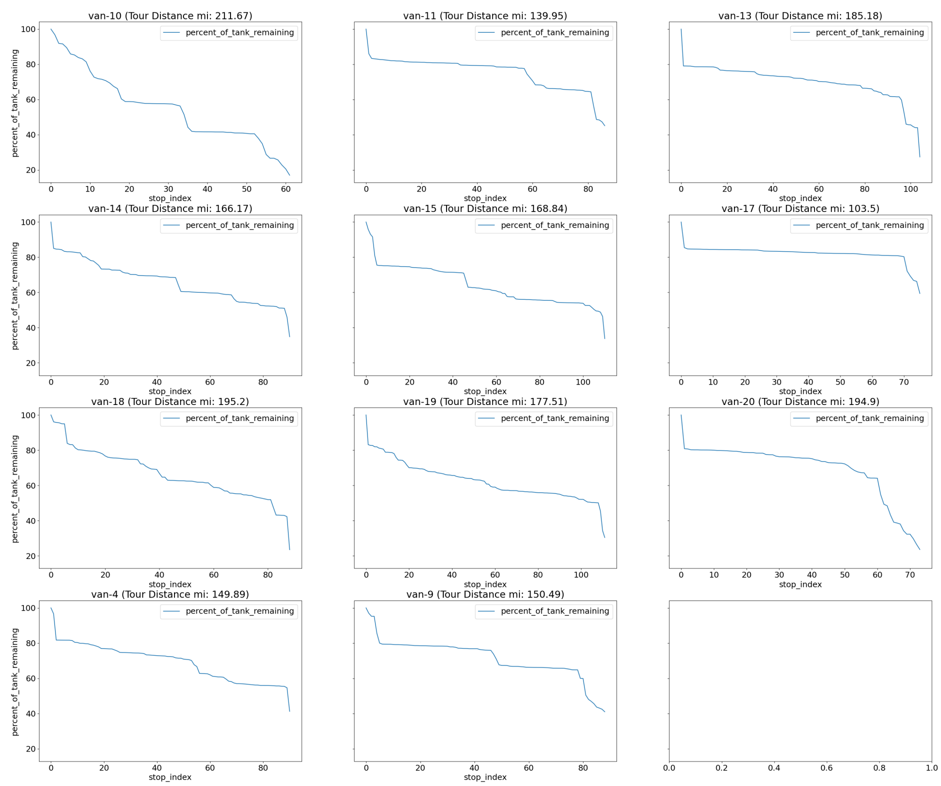
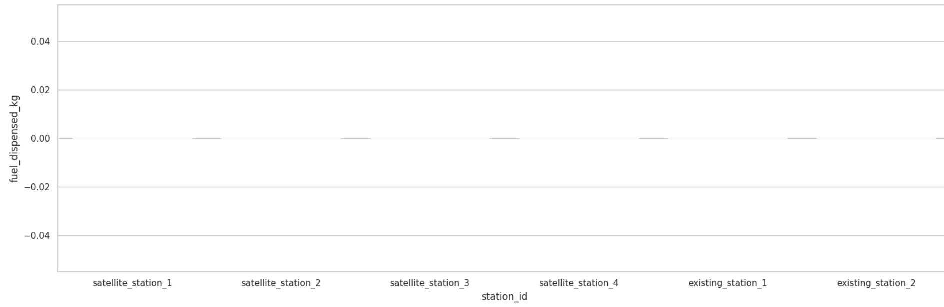


Figure B-42: Hydrogen Station Utilization – 15 Kg Delivery Van Storage and 4 Satellite Stations



Note: There is no usage of satellite or existing hydrogen stations with 15 kg of onboard storage

Figure B-43: Vehicle Fuel Use Profiles – 15 Kg of Delivery Van Storage and 4 Satellite Stations

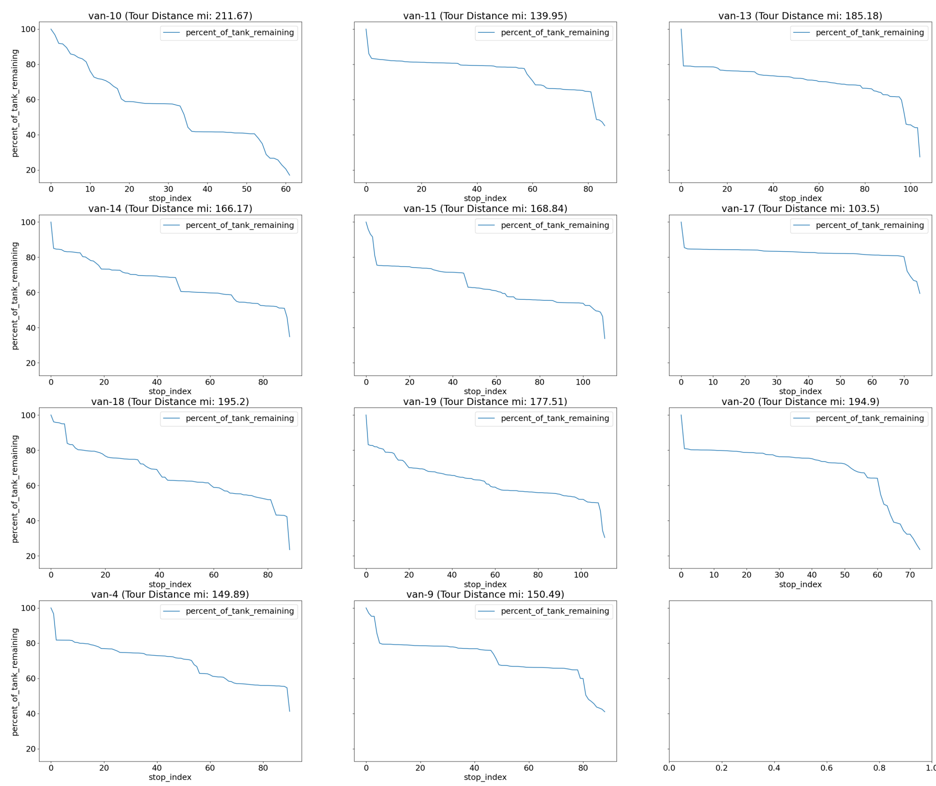
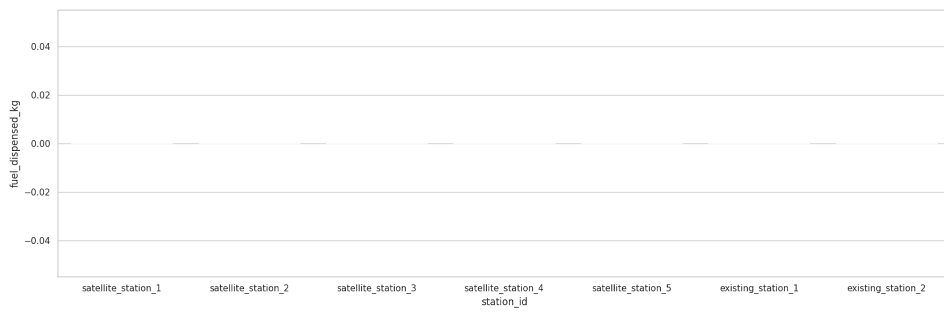


Figure B-44: Hydrogen Station Utilization – 15 Kg Delivery Van Storage and 5 Satellite Stations



Note: There is no usage of satellite or existing hydrogen stations with 15 kg of onboard storage

Figure B-45: Vehicle Fuel Use Profiles – 15 Kg of Delivery Van Storage and 5 Satellite Stations

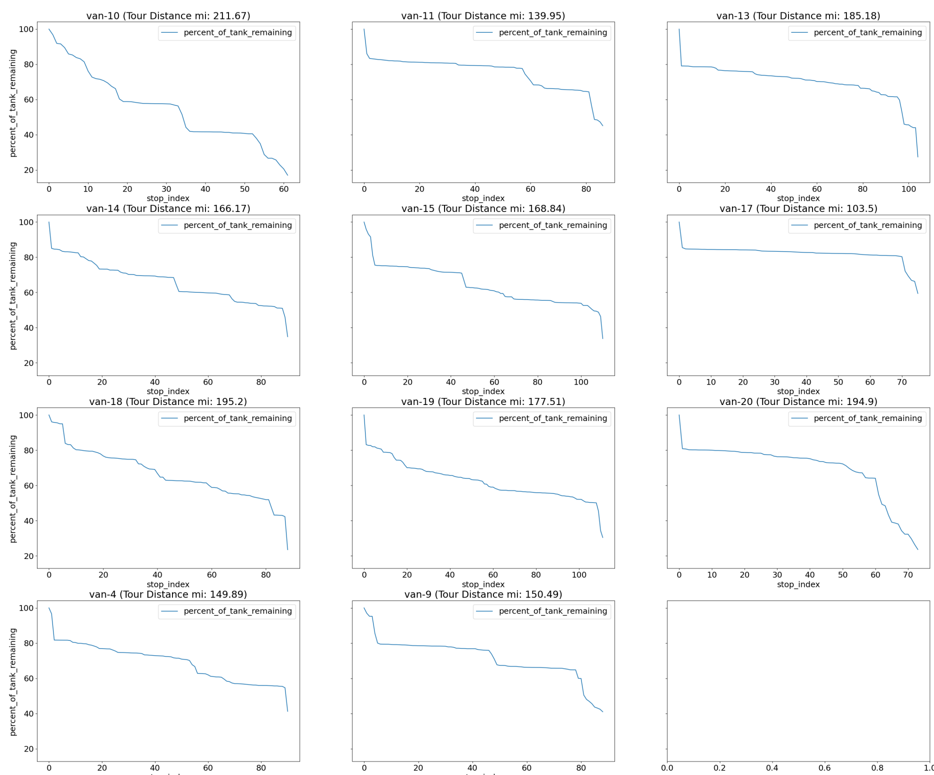
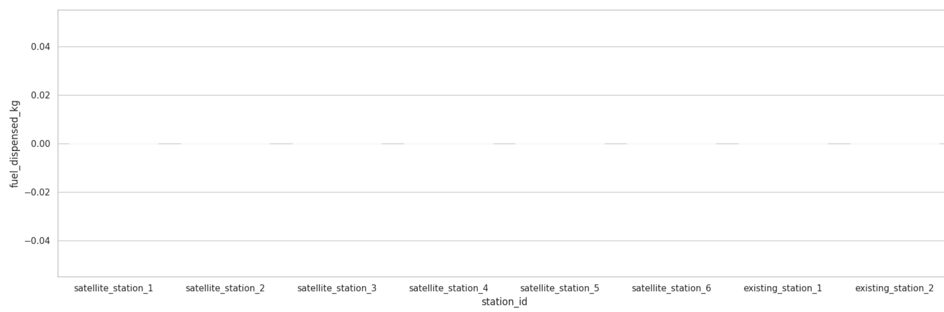


Figure B-46: Hydrogen Station Utilization – 15 Kg Delivery Van Storage and 6 Satellite Stations



Note: There is no usage of satellite or existing hydrogen stations with 15 kg of onboard storage

Figure B-47: Vehicle Fuel Use Profiles – 15 Kg of Delivery Van Storage and 6 Satellite Stations