20XX-01-XXXX

Hydrogen and Electric Charging Infrastructure for Heavy-Duty Trucks: A Nationally Scalable Megaregion Assessment

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Abstract

Decarbonizing regional and long-haul freight is challenging due to the limitations of battery-electric commercial vehicles and infrastructure constraints. Hydrogen fuel cell medium- and heavy-duty vehicles (MHDVs) offer a viable alternative, aligning with the decarbonization goals of the Department of Energy and commercial entities. Historically, alternative fuels like compressed natural gas and liquefied propane gas have faced slow adoption due to barriers like infrastructure availability. To avoid similar issues, effective planning and deploying zero-emission hydrogen fueling infrastructure is crucial. This research develops deployment plans for affordable, accessible, and sustainable hydrogen refueling stations, supporting stakeholders in the decarbonized commercial vehicle freight system. It aims to benefit underserved and rural energy-stressed communities by improving air quality, reducing noise pollution, and enhancing energy resiliency. This research also provides a blueprint for replacing diesel in over-the-road Class 8 freight truck applications with hydrogen fueling solutions. The study focuses on the Texas Triangle Megaregion (I-45, I-35, and I-10), the I-10 corridor between San Antonio, TX, and Los Angeles, CA, and the I-5/CA-99 corridors between Los Angeles, CA, and San Francisco, CA. This area represents a significant portion of U.S. heavy-duty freight movement, carrying ~8.5% of the national freight volume. Using the OR-AGENT (Optimal Regional Architecture Generation for Efficient National Transport) modeling framework, the study conducts an advanced assessment of commercial vehicles, road and freight networks, and energy systems. The framework integrates data on freight mobility, traffic, weather, and energy pathways to deliver a region-specific, optimized vehicles powertrain architectures, infrastructure deployment solutions, operational logistics, and energy pathways. By considering all vehicle origin-destination pairs utilizing these corridors and all feasible fueling station location options, the framework's genetic algorithm identifies the minimum number and optimal locations of hydrogen refueling stations, ensuring no vehicle is stranded. It also determines fuel schedules and quantities at each station. A roadmap for station deployment based on multiple adoption trajectories ensures a strategic rollout of hydrogen refueling infrastructure.

Introduction

Decarbonizing commercial vehicles through Zero or Near-Zero Emission Vehicle (ZEV and NZEV) technologies is essential, as the transportation sector remains the largest energy consumer in the United States, accounting for approximately 37% of all energy use in 2023 (see Figure) [1]. Transportation activities contributed 28.5% of U.S. greenhouse gas emissions in 2022, with light-duty trucks (including SUVs, pickup trucks, and minivans) being the largest source at 36.5%. Medium- and heavy-duty vehicles (MHDVs) were responsible for 22.9% of emissions, followed by passenger cars at 20.4% [2]. Other notable contributors included commercial aircraft (7.2%), pipelines (3.8%), ships and boats (2.8%), other aircraft (2.0%), and rail (2.0%). These emissions stem from the direct combustion of fossil fuels as well as indirect emissions from electricity use and non-energy sources like lubricants, refrigerants, and mobile air conditioners. Transitioning to ZEV and NZEV technologies can significantly reduce the carbon footprint of the commercial transportation sector, improve energy efficiency, and facilitate better integration with renewable energy. This transition is critical for meeting national and global decarbonization targets and promoting a cleaner, more sustainable transportation future, particularly in densely populated urban areas [3,4].

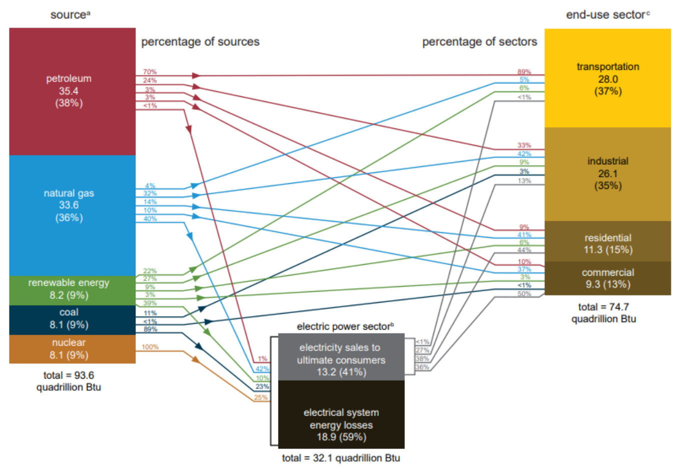

Figure 1. 2023 U.S. energy consumption by source and sector [1]

While battery-electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) may significantly lower emissions compared to internal combustion engines and are considered critical for decarbonizing MHDVs [5], they are not inherently zero-emission from a well-to-wheel perspective. Their environmental impact is influenced by the carbon intensity of electricity generation and hydrogen production, which may still rely on fossil fuels. Additionally, the lifecycle carbon footprint of these vehicles includes emissions from manufacturing, including materials like batteries, as well as end-of-life processes such as recycling and disposal. Integrating low-carbon energy sources upstream, such as renewable electricity and green hydrogen, can greatly enhance the sustainability of BEVs and FCEVs. This approach not only improves energy efficiency but also better aligns these technologies with renewable energy, enabling substantial reductions in well-to-wheel carbon emissions.

Scaling this effort requires strategic, forward-thinking planning to deploy clean fueling infrastructure efficiently, particularly along key freight corridors, ports, and depots. MHDVs' significant energy demands necessitate coordinated efforts among private sector stakeholders, regional authorities, and policymakers to ensure reliable access to charging and hydrogen refueling stations [5]. Integrated planning will streamline deployment, minimize grid impacts, and align with environmental equity and justice (EEJ) goals, ultimately accelerating infrastructure readiness and supporting broader decarbonization targets.

In alignment with this vision, the National Zero-Emission Freight Corridor Strategy, unveiled in March 2024 by the Joint Office of Energy and Transportation, DOE, DOT, and EPA, outlines a comprehensive strategy for deploying zero-emission infrastructure for medium- and heavy-duty vehicles through 2040 [5]. It focuses on strategically directing public investments to catalyze private-sector advancements, streamline energy regulatory processes, align industrial efforts, and improve air quality in communities disproportionately impacted by diesel emissions. Complementing this initiative is the Regional Clean Hydrogen Hubs program (H2Hubs), established in 2022 with $7 billion allocated to create seven regional hydrogen hubs [6]. These hubs aim to link hydrogen producers, users, and infrastructure, fostering regional ecosystems for clean hydrogen adoption—see Figure 2. Additionally, the National Electric Vehicle Infrastructure (NEVI) Program, funded with $5 billion under the IIJA, focuses on building a nationwide network of BEV fast-charging stations along interstate highways and major corridors [7,8]. The program emphasizes equity, accessibility, and technical reliability, ensuring widespread and fair distribution of charging infrastructure, including in underserved areas. These initiatives collectively represent a transformative approach to reducing greenhouse gas emissions and advancing sustainable transportation across the United States.

Figure 2. Selected regional clear hydrogen hubs [6] and the H2LA corridor network

Despite recent advances, significant challenges persist in determining the optimal applications of hydrogen power versus BEV solutions for commercial transportation, particularly long-haul freight. Existing programs provide high-level strategies for hydrogen and charging infrastructure deployment but lack detailed, actionable roadmaps to address the unique needs of freight operations. For example, emerging *destination charging* solutions—designed to supply trucks with sufficient energy to complete their routes—are beginning to gain traction but remain geographically limited [9,10]. In contrast, *enroute* high-power charging infrastructure along key freight corridors, truck stops, and urban logistics hubs is sparse and fails to meet the significant energy demands of long-haul trucking [11]. Localized and small-scale "micro-corridors" are emerging in regions like the U.S. Southwest (e.g., I-15) and critical logistics hubs, such as the Port of Long Beach and surrounding warehouse districts [9,10,11]. These efforts, however, often serve only select truck fleets, require operational compromises, and remain fragmented without a cohesive, scalable framework [12,13]. Addressing these infrastructure gaps will require coordinated, national approaches that integrate diverse stakeholders—energy providers, fleet operators, logistics hubs, and policymakers—while balancing the demands of scalability, energy reliability, and cost-efficiency to support a viable zero-emission freight future.

This research develops a nationally scalable methodology for deploying hydrogen refueling and electric charging infrastructure and applies it to key freight corridors essential for commercial vehicle electrification in the US Southwest. These corridors include the Texas Triangle Megaregion, the I-10 corridor from Houston to the Ports of Los Angeles/Long Beach, and the I-5/CA-99 route connecting Los Angeles and San Francisco—see Figure 2. Known as the Houston to Los Angeles (H2LA) corridor, these routes are critical for U.S. freight movement, connecting major ports and transportation hubs—see Figure 3 [14]. The Houston area is positioned to become a leading hub for clean hydrogen production, supplying fuel to this network [15]. As a cornerstone of the U.S. Zero-Emission Freight Corridor Strategy, the H2LA corridor accounts for approximately 25% of Phase II efforts, linking the California and Gulf Coast Hydrogen Hubs with other national hubs to ensure supply-demand balance and enable sustainable freight transportation.

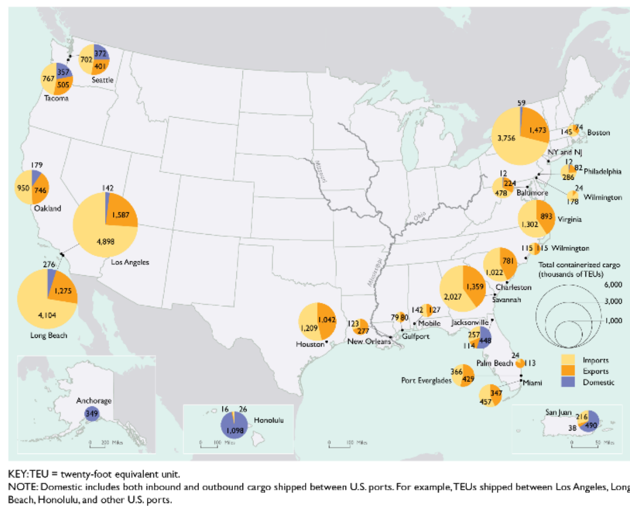

Figure 3. Top 25 water ports by TEU [14]

In this paper, we introduce an innovative method for siting alternative fuel stations specifically tailored for commercial vehicles, addressing the unique challenges posed by hydrogen fueling stations and electric vehicle charging infrastructure. This method is designed to align with the infrastructure demands of major national programs, such as the National Zero-Emission Freight Corridor Strategy and the NEVI programs. By strategically optimizing the placement of fueling and charging stations, the approach ensures that medium- and heavy-duty vehicles have efficient and reliable access to clean energy along key freight corridors, thus facilitating uninterrupted freight movement and connecting critical regions. This method is essential in the broader effort to advance clean energy infrastructure and supports the widespread deployment of zero-emission vehicles, ultimately contributing to national and global decarbonization objectives. It has been successfully applied to the H2LA corridor, a key freight route, and is readily scalable to other corridors and regions worldwide. The strength of this method lies in its use of detailed multi-agent vehicle modeling within real-world, complex environments. Through a systematic optimization process, supported by high-resolution data, the method provides accurate geo-located solutions for siting energy replenishment facilities along key transport routes. This approach not only ensures operational efficiency but also maximizes the economic and environmental benefits of zero-emission vehicle adoption.

Figure 4. Texas Triangle Megaregion, I-10 corridor, and I-5/CA-99 corridors of interest

Year	Type	Truck Kton-miles (Annual)				
		(A) Texas Triangl	(B) I10 corridor	A + B	US	% Share of A + B
2017	Single	28,533,150	9,083,618	37,616,768	560,873,845	6.71%
2017	Combination	83,122,180	33,942,284	117,064,464	1,538,794,017	7.61%
2017	**Total**	**111,655,327**	**43,025,903**	**154,681,230**	**2,099,667,813**	**7.37%**
		Truck VMT (Daily)				
		(A) Texas Triangl	(B) I10 corridor	A + B	US	% Share of A + B
		4,175,820	1,634,757	5,810,576	88,740,317	6.55%
		8,853,270	3,790,342	12,643,612	172,422,852	7.33%
		13,029,089	**5,425,101**	**18,454,190**	**261,163,164**	**7.07%**

Figure 5. Summary of freight movement statistics in Texas Triangle and I-10 region [17]

Megaregions are large, interconnected geographic areas that encompass multiple metropolitan areas and surrounding regions, characterized by economic integration, extensive transportation networks, shared resources and challenges, and significant urban growth [16]. They feature high economic interdependence driven by shared industries and supply chains, well-developed infrastructure for the movement of people and goods, and common environmental and planning issues that span across cities and regions. Megaregions play a critical role in regional planning, economic development, and infrastructure needs at a larger scale than individual cities. The Texas Triangle Megaregion, home to over 70% of Texas' population—nearly 21 million people—includes five of the 20 largest U.S. cities and is anchored by Austin, Dallas–Fort Worth, Houston, and San Antonio, connected by Interstates 45, 10, and 35 (Figure 4). This region handles 306 million ton-miles of daily truck freight, representing 5.3% of total U.S. truck freight activity, supported by 35,700 miles of daily commercial vehicle VMT. Additionally, the I-10 freight corridor from San Antonio to Los Angeles carries 118 million ton-miles of daily freight, contributing 2.1% of the U.S. truck freight volume (Figure 5) [17]. Together, the Texas Triangle and I-10 corridor are vital to the national supply chain, facilitating goods movement between Texas, California, and the broader U.S. economy. This makes the region a priority for infrastructure development, particularly for expanding clean fuel technologies like hydrogen and electricity to support sustainable freight systems.

This paper is structured as follows. In the next section, we present the overall methodology developed for this research, detailing the approach and framework used in the siting process. Following that, we explore the results and analysis, examining the outcomes of the study and their implications. We then focus on key attributes of the solutions, discussing the differences between Fuel Cell Electric Vehicles (FCEVs) and hydrogen refueling infrastructure, compared to BEVs and electric charging infrastructure. Finally, we conclude with remarks summarizing the findings and offering insights for future work.

Methodology

Oak Ridge National Laboratory (ORNL) has developed the OR-AGENT (Optimal Regional Architecture Generation for Efficient National Transport) framework, an advanced system-of-systems analysis platform for commercial road freight and energy systems [18,19,20]—see Figure 6. OR-AGENT uses parametric optimization to design vehicle powertrains, local energy dispensing systems (e.g., refueling/recharging stations), and regional energy infrastructure, including the electric grid, distributed energy resources (DER), and grid-scale storage. It addresses multiple objectives such as minimizing system costs, total cost of ownership (TCO), and carbon emissions, while remaining adaptable to stakeholder needs. The framework integrates data across subsystems, including vehicle powertrains, freight logistics, traffic, weather, and energy pathways, to produce region-specific, seasonally optimized solutions for vehicle and infrastructure deployment. By considering the diverse priorities of stakeholders—fleet operators, equipment suppliers, utilities, and planners—OR-AGENT offers a holistic, constraint-aware approach to planning. Unlike traditional isolated methods, it aligns vehicle and energy infrastructure development under a unified strategy. While this study focuses on heavy-duty trucks and hydrogen/electric refueling infrastructure, OR-AGENT's versatility extends to various energy solutions and vehicle types, including diesel, natural gas, and off-road applications. It serves as a strategic planning tool for governments, industries, and energy providers, enabling sustainable, future-proof transport and energy systems. Figure 6 illustrates the workflow, which reflects a subset of OR-AGENT's broader capabilities.

To summarize, the key outputs of this model include:

- Vehicle powertrain architecture recommendations
- Local infrastructure architecture (type, location, quantities of chargers/ refueling systems)
- Regional infrastructure arch. (grid and DER asset deployment)

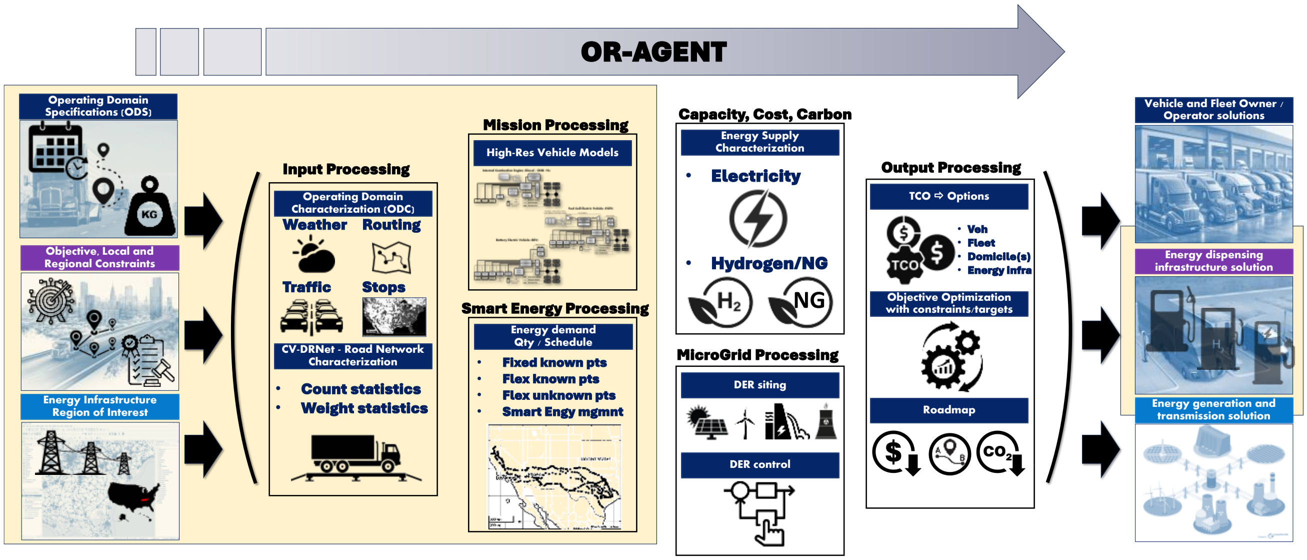

Figure 6. OR-AGENT workflow construct (highlighted region is the focus of this research paper)

Rather than delve into the details of each subsystem illustrated in Figure 6, we provide only a brief overview, as the majority of these details have already been extensively covered in previous publications or submissions and will be highlighted as such [20]. In addition, for the scope of this paper not all subsystems have been exercised and will be indicated as such in the subsequent descriptions (yellow highlighted region in Figure 6).

A. **Input requirements**:

- **Operating Domain Specifications (ODS):** Every study on an interconnected vehicle system begins by defining the specific customer use case being investigated. In this study, the focus is on heavy-duty freight trucks operating within the H2LA corridors. Key parameters include the vehicle type (class/weight), origin-destination (OD) coordinates (if available in GPS form), and the departure/operating schedules of the trucks. To avoid complications arising from time zone differences, all vehicle movements are modeled in Coordinated Universal Time (UTC), with the option to convert results back to local time if requested by stakeholders. For this study, the vehicle type is restricted to Class 8 combination tractor-trailer units, representing the primary freight movers in this corridor. Since we are analyzing a broad region of freight movement along the H2LA corridor, specific customer OD inputs are not directly available. Instead, these are derived as part of the *Operating Domain Characterization (ODC) Input processing*, which will be discussed later. Truck departure schedules are aligned with publicly available data on heavy-duty truck movements from ports, as illustrated in Figure 7 [21]. Future iterations will refine these inputs by incorporating more region-specific information based on higher-resolution data, as outlined in the ODC Input processing step.

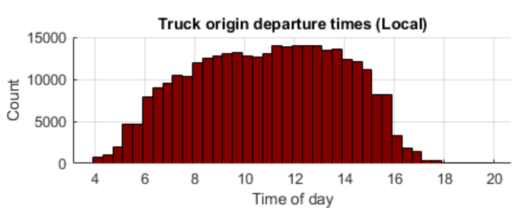

Figure 7. Assumed truck departure times from origins

- **Objective Function with Local and Regional Constraints**: In the context of this study, the objective function serves as the mathematical representation of the primary stakeholder goal, which is to optimize key attributes of the output such as the TCO, optimize the domicile infrastructure, minimize the effective system carbon emissions, or some other formulation. The optimization is subject to local and regional constraints. Local constraints include factors like grid capacity at specific station locations, land availability, fleet behind the fence infrastructure limitations or public access infrastructure siting constraints, and proximity to major freight routes or industrial hubs. These factors affect how many stations can be built, their size, and the available energy or hydrogen supply. On a regional level, constraints encompass broader factors like regulatory policies (ex. Advanced Clean Fleet), regional energy supply limitations, environmental impacts, and coordination across state boundaries. Constraints can either be limits or exclusions applied to a parametric search space of solutions, or targets that must be achieved. By balancing these local and regional constraints within the objective function, the model aims to provide a feasible, efficient infrastructure network that aligns with both immediate operational needs and long-term regional goals for decarbonization and sustainable freight transport. For the H2LA corridors the goal is to **minimize the total number of stations** while meeting vehicle demand. The optimization of this will be discussed in the **Output Processing step**.

- **Energy Infrastructure in the Region of Interest**: A key step in planning alternative fuel stations, especially hydrogen fueling and electric vehicle charging stations, is understanding the region where these stations will be located. This requires assessing the energy infrastructure in the area and how it connects to broader networks, such as roads, electric grids, and pipelines. Defining these boundaries can be challenging since regions are part of larger, interconnected systems that often extend beyond state and national borders. The complexity arises because energy infrastructure—like power grids and hydrogen production networks—operates across systems that need to be considered when placing stations. For example, a BEV charging station depends on local grid capacity but may also rely on power plants far outside the region. Similarly, hydrogen fueling stations are linked to production facilities through pipelines or long-distance transport. Regions are shaped by overlapping systems that must be coordinated. Road networks for commercial vehicles often span multiple utility areas, each with its own regulations and limits. Local factors such as economic activity, population, and freight movement further complicate the task of setting clear boundaries without overextending them. To manage this complexity, stakeholders should integrate data from transportation models, grid assessments, and logistics to define practical boundaries. A multi-layered approach is needed—one that considers both local infrastructure and broader networks linking the region to neighboring areas. This ensures a more resilient solution, supporting the smooth operation of alternative fuel vehicles and aligning with national decarbonization goals. For the H2LA corridor, Freight Analysis Framework (FAF) and National Household Travel Survey (NHTS) data [17,22] were used to identify the region of interest, shown in Figure 8, where the impact of commercial freight diminishes significantly outside of this area. This approach ensures focused infrastructure development without expanding the region unnecessarily.

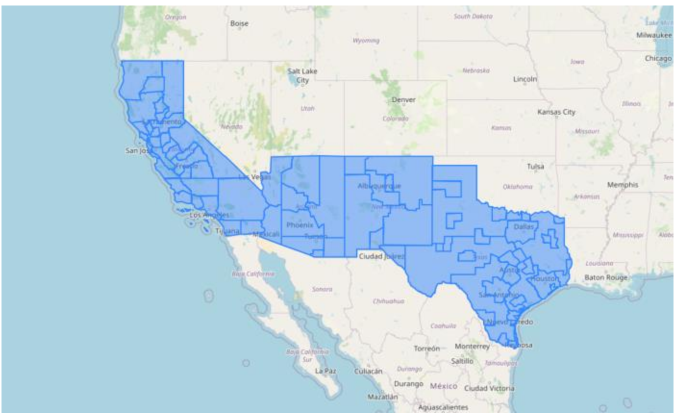

Figure 8. H2LA region of interest approximated from FAF/NHTS. Sub-boundaries indicate NHTS relevant zones (583 zones nationally and 76 along the H2LA corridor)

B. Input Processing – Operating Domain Characterization

- **Weather Processing:** Ambient conditions such as air temperature and pressure can significantly influence vehicle energy consumption by affecting various components and driving loads. These factors can alter the energy required for thermal management systems, accessory loads, and even change air density, impacting aerodynamic drag on the vehicle. Previous research has shown that seasonal variations alone can cause up to a 20% difference in energy consumption on the same route [23]. In this H2LA corridor study, weather-related factors such as temperature, air density, and wind speed/direction are incorporated using data from the National Oceanic and Atmospheric Administration (NOAA), alongside vehicle counts and schedules (departure/arrival times) for port-related traffic along each route. This data, developed through prior work [24], feeds into a comprehensive dataset integrated into an automated process, streamlining the establishment of ODS for specific ports or fleet domiciles. The factors used to develop the ODS are regionally and temporally specific, ensuring that the model captures the local variations that affect vehicle performance, making it adaptable for future studies.
- **Routing:** When OD information is provided, including GPS coordinates and schedules, direct vehicle routing can be established using tools such as the Google Directions API for general vehicle navigation or PC*Miler[1] for truck-specific directions. These GPS coordinates are mapped to elevation and road speed limits through the HERE Technologies Map Attributes API[2]. To calculate the directional slope, a MATLAB® acausal filter function, *filtfilt* is used along with a max slope clamp based on US highway engineering limits [25]. To efficiently handle large sets of OD pairs, this process has been automated within MATLAB, where HERE Technologies' Road Elevation data is stored in a comprehensive database, built through systematic screening of Level 1 to 4 roads (functional classification) across the U.S.

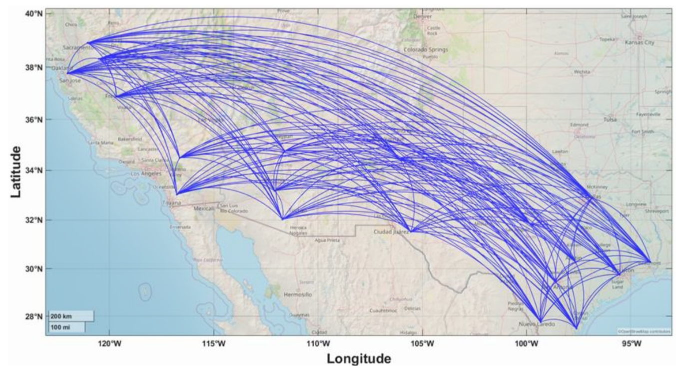

Figure 9. H2LA ODs approximated from FAF/NHTS

In cases where OD information is not initially provided, several other data sources can be used to generate this information. For instance, StreetLight Data[3] is a commonly used provider of highly granular vehicle OD information, broken down by Census Block Zones, covering about 217,526 zones nationwide. This dataset provides detailed insights into vehicle type, schedules, and other movement attributes. Alternatively, the OR-AGENT framework can generate a statistical view of OD patterns based on FAF and NHTS data, providing insights on OD distributions by calendar quarter and by FAF zones, as detailed in [26]. As indicated above, for the H2LA corridor in this paper, FAF and NHTS data are used to determine the statistical OD in the region of interest. See Figure 9, Figure 10, and Figure 11 for the OD and routing. The process of integrating higher resolution StreetLight data is underway.

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[1] PC*Miler, https://www.truckingoffice.com/lp/pc-miler/
[2] HERE Technologies Map Attributes API, https://www.here.com/developer/
[3] StreetLight Data, https://www.streetlightdata.com/

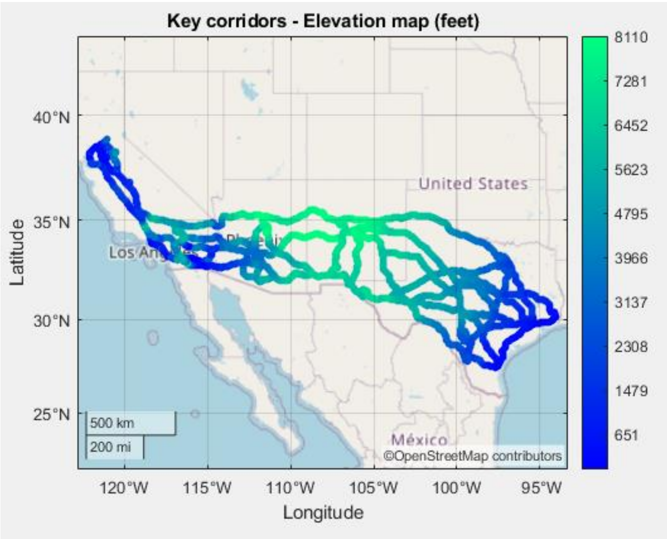


Figure 10. Routes and elevations with additional roads of interest

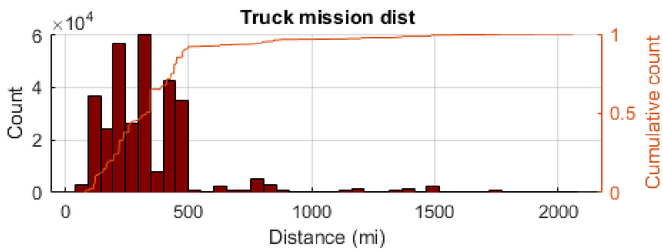
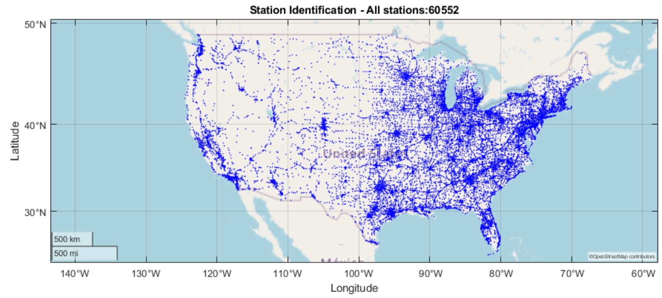


Figure 11. OD route distance statistics

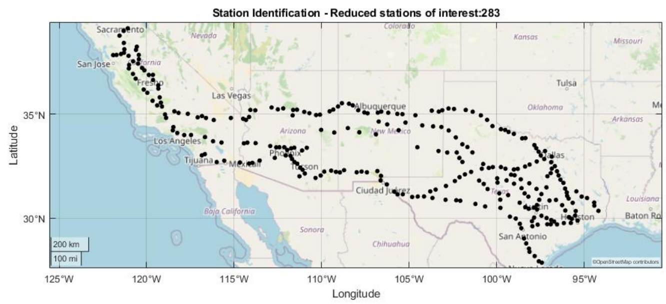
- **Admissible Stops:** Admissible known or unknown stops are developed next. If the list of stops has been provided (known) as part of the constraint space (for example all current public access heavy-duty refueling stations or all private vehicle domiciles within a fleet network may be candidates for future zero-emission vehicle recharging or refueling points), then stations within some constraint may be defined as candidates. For the H2LA corridor the stops are the current public access heavy duty truck diesel refueling stations with d = 5 miles—impact shown in Figure 12.

  If the list of stops is not provided but rather need to be discovered, then a list of candidate stop locations is generated by simply dividing up the region into a raster scan of candidate sites defined by a specific geometric construct For example, the region may be subdivided into an array of sub regions each measuring a predefined dLatitude x dLongitude or dL_1(m) x dL_2(m) These become the candidate locations for the refueling/recharging stations, and the reduction process described above may now be applied.

- **Traffic**: Accurately modeling naturalistic driving behavior hinges on effectively capturing traffic patterns. The approach being developed leverages HERE Technologies' traffic analytics, which provide average vehicle speed data in 15-minute intervals over the course of a week for any specific location (https://www.here.com/developer). While this data may not be highly granular, it offers a practical means of synthesizing realistic driving conditions based on real-world observations. By incorporating these traffic dynamics into the model, the system can better reflect the variability in vehicle speeds due to congestion, road conditions, and time-of-day effects, which is crucial for modeling energy consumption and operational schedules. Though still in development, this traffic integration within the OR-AGENT framework has the potential to significantly enhance the accuracy of naturalistic driving simulations. As such this feature is not yet incorporated into the H2LA corridor analysis. Further refinements and results from this work will be detailed in future iterations of this research. Other data source for similar but higher granularity data is being explored, including RITIS (https://ritis.org/login?r=Lw==).



(a) *All Heavy-Duty truck diesel refueling stations (Geotab-2021 https://www.gpsfms.com/)*



(b) *Reduced candidate stations within 5 miles of the H2LA corridor and broader roads of interest*

Figure 12. H2LA region of interest candidate refueling/recharging stations

- **Count and Weight Statistics:** Vehicle weight and classification data are sourced from the FAF and the Truck Monitoring and Analysis System (TMAS), both of which aggregate real-world measurements from various monitoring stations [19]. These stations, managed by state highway and transportation agencies, collect essential data on vehicle volume, classification, and weight [19,27]. Whether permanent or temporary, these stations play a vital role in understanding roadway usage. A key technology used is the Weigh-in-Motion (WIM) system, which captures vehicle characteristics, such as weight, axle configurations, and more, as vehicles pass at regular highway speeds. Unlike static scales that require trucks to stop, WIM systems collect dynamic data, including axle loads, spacing, speed, direction, FHWA vehicle classification, and time stamps, without interrupting traffic flow—see Figure 13. Operating continuously, WIM systems provide a rich dataset for analyzing truck volumes and weights, offering critical insights for transportation planning and management. Previous work reported by the authors have demonstrated the potential for reconstructing traffic flows across national highways using limited vehicle classification data from the fixed stations [27]. The OR-AGENT framework leverages this by using an iterative process to impute traffic volume and vehicle class information across broader traffic networks, further enhancing transportation analysis capabilities. Future refinement of this process for weight imputation is currently underway.

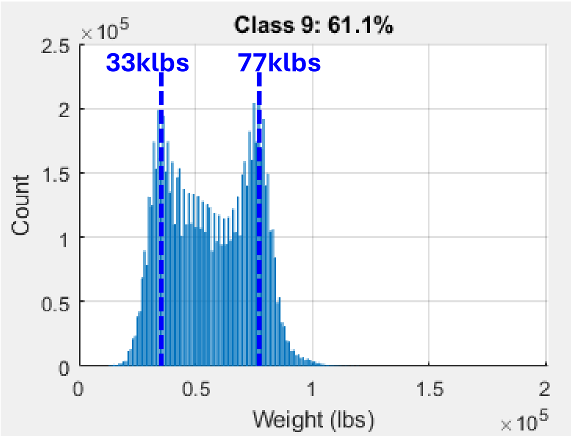


Figure 13. Texas triangle HD tractor-trailer weight distributions (bimodal peaks noted at 33klbs (empty tractor trailer) and 77klbs

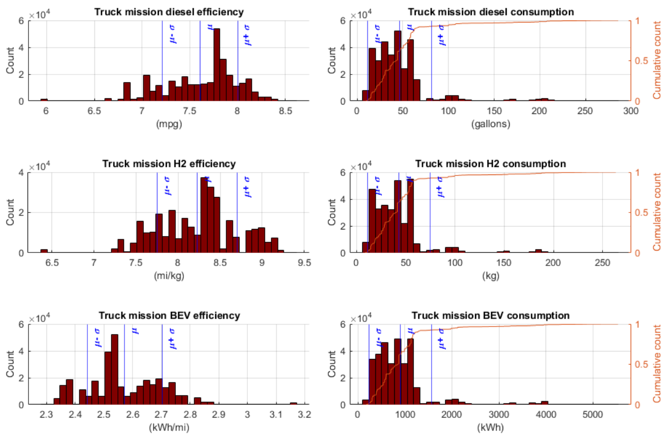


Figure 14. H2LA region of interest route energy efficiency for diesel, FCEV and BEV powertrains

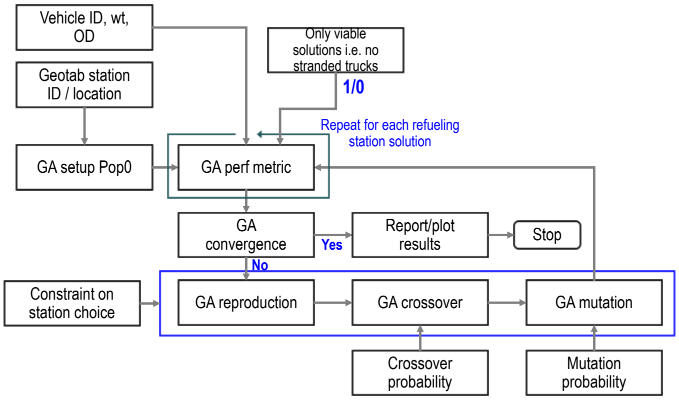
C. **Mission Processing:** This process relies on high-resolution vehicle and powertrain models that simulate the key dynamics of vehicles operating in environments described by the ODC. Although the detailed development of these vehicle models falls outside the scope of this paper, it has been extensively covered in prior work [23]. In brief, we have created a 1-D model for heavy-duty diesel, BEV, and FCEV powertrains. The BEV and FCEV architectures are based on a tandem e-axle configuration, with 250 kW electric motors powering each axle. These e-axles feature electric motors integrated into three-speed gearboxes, with additional gear reductions at the axle differential and wheel ends—mirroring state-of-the-art technology for heavy-duty electric trucks. The powertrain models use a forward-looking, quasi-static approach enhanced driver model [27]. The aerodynamic model adjusts the drag coefficient based on truck configuration (e.g., with or without a trailer) and the yaw angle relative to the wind direction [29]. The tire rolling resistance model accounts for changes in rolling resistance based on vehicle speed and tire temperature, with tire thermal dynamics approximated using a first-order transfer function [30]. The vehicle simulator includes auxiliary components such as cabin heating, ventilation, air conditioning (HVAC) compressors, battery thermal management systems, and pneumatic brake pumps. The energy consumption of these systems is modeled using a duty cycle-based approach, accounting for the influence of ambient conditions on power usage [31,32]. Battery and charger models of similar resolution are also incorporated into the simulator, capturing the electrical, thermal, and aging dynamics of various battery chemistries. This integrated model calculates the energy consumption of trucks over an entire year, factoring in seasonal variations in elevation, road grade, ambient temperature, and air density across the multiple routes identified in the ODC (Figure 14). Battery energy and fuel cell power capacity assumptions will be described in the *Results*.

D. **Smart Energy Processing:** As outlined in the *Admissible Stops* section, energy processing at both fixed and flexible stopping points can be determined based on the specific mission requirements.

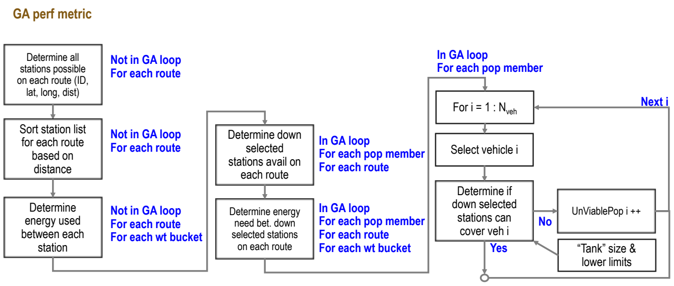
- **Fixed Stopping Points**: To calculate energy needs at fixed stopping points, vehicle schedules, trip energy demands, and stop dwell times are combined, assuming vehicles start their day with full batteries or hydrogen tanks. The configuration of dispensers or chargers then translates these energy requirements into power demand at each stop. By aggregating the energy consumption across all vehicles over the year, a demand projection can be created. However, the challenge lies in the level of detail available for vehicle trips—specifically, the entire sequence of trips for a vehicle, not just individual origin-destination pairs. If the sequence is known, energy demand can be accurately traced. If not, assumptions about energy replenishment at each stop must be made, which can be approached by evaluating trips independently or considering factors like hours of service, schedules, daily miles, and energy required for each leg of the trip. This more complex modeling offers a comprehensive energy demand assessment across various operational scenarios. Further details are available in prior work [20].

- **Flexible Stopping Points:** for refueling or recharging trucks introduce dynamic decision-making compared to fixed stops. Trucks can choose from a list of potential stations during their trip, rather than adhering to a predetermined set. Each trip begins with a clear destination, which is the last stop where the vehicle must arrive with enough energy. Along the way, the truck may need to stop at intermediate stations to ensure it has sufficient energy to complete the journey. The need for a stop is determined by monitoring energy consumption, and if energy is insufficient, a candidate refueling or charging site is selected. Optimization focuses on minimizing the number of stops, balancing factors like distance, energy consumption, station availability, and sustainability. The goal is to identify the most efficient network of stations to maintain energy reserves and minimize CO2 emissions while avoiding operational disruptions. The model ensures that the truck completes its trip efficiently, recommending an optimal set of stops based on operational and environmental goals.

In the H2LA corridor model, the objective function is to minimize the number of available stations in the route network to leave no truck trip stranded (or minimize the number the of stranded trucks), using a flexible set of known stop locations. This is accomplished with a genetic algorithm (GA)—see Figure 15.



(a) Overall GA workflow



(b) GA performance metric workflow

Figure 15. H2LA smart energy processing optimization using genetic algorithm

- **Smart Charge Management (SCM)** features focus on optimizing the charging process for electric vehicle batteries to enhance efficiency, minimize degradation, and align with grid constraints. At present these are under development for the OR-AGENT model framework (including extensions for real time controls) and will be reported out in future publications..

E. Infrastructure Capacity, Cost, Carbon processing

- **Grid Capacity:** To assess grid capacity at a specific location for a point of use, several key steps are followed. First, nearby energy generation plants are checked for activity and their ability to provide power. Next, the available transformer capacity is reviewed to ensure it can handle additional loads. Line capacity is evaluated to ensure it can support the necessary power flow. The infrastructure from substations to end-user sites is also examined to confirm that power can reach distribution substations, excluding the final 480V lines. Substation performance data from the North American Energy Resilience Model (NAERM[4]), developed by ORNL, is used to evaluate grid resilience and capacity. This model provides a comprehensive assessment of energy capacity for each charging location, ensuring that substations within a 15-mile radius can provide the required energy. The grid capacity assessment, such as for the H2LA corridor, is based on aggregate data from substations within this range (see Figure 16)

- **Grid Carbon Intensity:** Grid carbon intensity, measured in grams of CO_2 per kilowatt-hour (gCO_2/kWh), is directly tied to the energy sources supplying the grid. Transitioning from diesel or fossil fuels to electricity does not eliminate a vehicle's carbon footprint but shifts it to the grid, which still relies on carbon-emitting sources such as coal, natural gas, and oil. Even low-carbon sources like nuclear, solar, wind, and hydroelectric power have non-zero carbon intensities due to factors like raw material production and energy transfer losses. By 2021, 40.6% of U.S. electricity was derived from renewable and nuclear sources, up from 35.8% in 2016 [33]. However, carbon intensity varies non-linearly due to seasonal changes, demand fluctuations, and energy exchanges between Balancing Authorities (BAs). To estimate the carbon intensity of added loads, a novel approach uses historical data on grid carbon intensity and demand, tailored to each region [20].

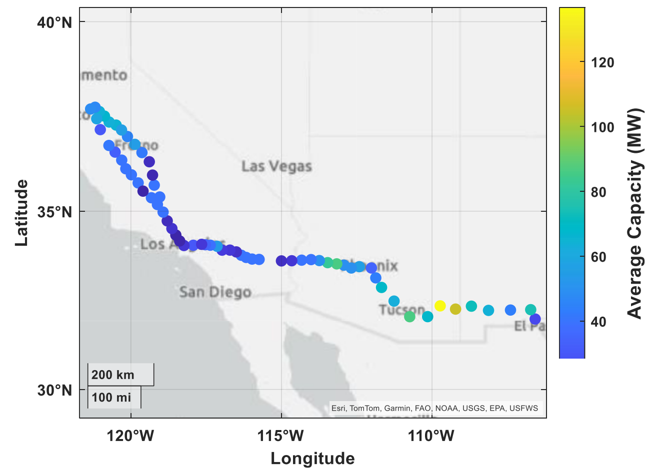


Figure 16. H2LA regional substations and their excess capacity

- **Hydrogen and Natural Gas – Capacity, Cost and Carbon** assessment tool development is currently under exploratory discussions and will be reported out in future publications. This includes using the electric grid information for electrolytic hydrogen generation. Further for the scope of this H2LA corridor paper, the infrastructure capacity, cost and carbon impact is not included but will be included in future publications.

F. Microgrid Processing

The microgrid capabilities will enhance energy resilience, sustainability, and efficiency for the charging infrastructure. Key features include: Renewable Energy Integration, Energy Storage Solutions, Grid Independence and Resilience, Demand Response and Load Management, Seamless Integration with Charging Infrastructure, Support for Electrification Goals.

Overall, microgrid capabilities will create a sustainable, efficient, and resilient energy solution for the charging infrastructure, contributing to the goals of reducing greenhouse gas emissions and supporting the electrification of the trucking industry. To develop an integrated microgrid system utilizing DER requires two key steps. First, the capabilities of the DER assets and their

[4] https://www.energy.gov/oe/north-american-energy-resilience-model

siting must be evaluated and strategically aligned—detailed in [34]. Second, the interaction between the DER assets and grid electricity must be optimized to create the most efficient and reliable energy mix—detailed in [35].

G. Output Processing

Final processing to determine the critical outputs of this process are divided into three efforts: TCO development, Objective optimization, and Roadmap development with details developed in [36].

- **TCO Development:** A comprehensive TCO tool has been developed to evaluate the techno-economic implications of transitioning vehicles and their supporting infrastructure. This innovative tool analyzes various energy transition pathways within the proposed framework, considering both vehicles and infrastructure holistically. As shown in Figure 17, the model is structured into three discrete but interconnected modules—Vehicle, "Local" Infrastructure, and "Regional" Infrastructure—each encapsulating distinct elements essential to the comprehensive evaluation of decarbonization strategies.

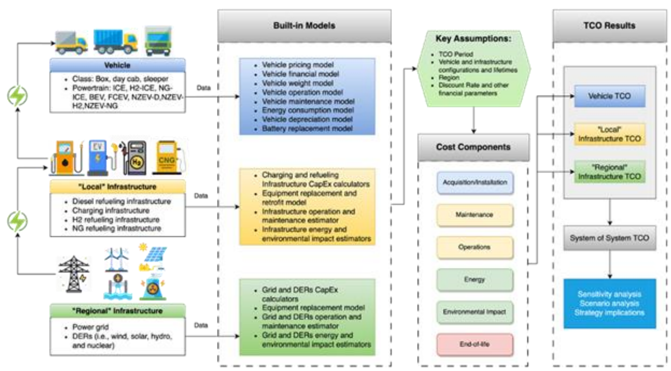


Figure 17. Overview of the interconnected system TCO tool

Objective Optimization: The parametric study provides valuable insights by analyzing specific option studies. When these studies comprehensively address the problem, the optimal solution—defined by a "cost function"—can be readily identified. However, if the search space, which includes vehicle types, powertrains, domicile/truck stop configurations, and energy backbone architectures, becomes too large, a more advanced optimization process is required. This process follows a structured, five-step nested framework, as illustrated in Figure 18 [20]. First, the Total Cost of Ownership (TCO) and CO2 emissions are evaluated for each vehicle-powertrain combination. Next, a Mixed Integer Linear Programming (MILP) approach optimizes the fleet mix to achieve specific targets, such as cost minimization, Zero Emission Vehicle (ZEV) compliance, and CO2 reduction, while accounting for conversion penalties tied to the remaining life of powertrains. Steps three and four integrate cascading infrastructure costs, such as truck stop upgrades and energy backbone improvements, into vehicle TCOs, distributing these costs based on vehicle utilization and recovery periods. Finally, a Genetic Algorithm (GA) minimizes overall system costs by optimizing vehicle configurations and infrastructure while meeting constraints, including fleet composition, emissions targets, and budget limitations. This process strikes a balance between cost efficiency and operational sustainability, enabling gradual and rational fleet transitions over time.

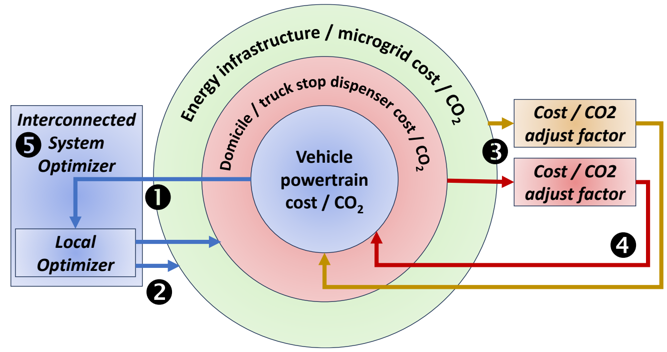


Figure 18. Simplified nested optimization process (five steps indicated)

- **Roadmap Development**: After completing the single-year co-optimization—where the fleet of vehicles, powertrain configurations, truck stop architecture, and energy backbone infrastructure are optimized for that year—a roadmap is generated to project how these elements will evolve year by year. This roadmap offers a clear, structured view of how the transportation system will transition over time, considering both technical and economic factors, while satisfying key constraints such as budgetary limitations, carbon emission targets, or ZEV mandates.

Results and Analysis

A. Performance Impact Assessment

Using the FAF data to generate OD information, we identified the average annual truck trips and VMT, as illustrated in Figure 19. Based on this data Figure 20 presents the expected well-to-wheel CO2 emissions for various truck propulsion systems assuming a complete conversion of these vehicles from diesel to alternative zero-emission powertrains. Key observations include:

1. Diesel Trucks: The highest level of CO_2 emissions comes from diesel trucks, with emissions close to 50 MT/yr. This is expected, given that diesel trucks rely heavily on fossil fuels, leading to higher carbon emissions.

2. BEV: The "BEV 386g/kWh" bar, based on the US electric grid average carbon intensity, shows a significant reduction in CO_2 emissions compared to diesel, indicating that electric trucks, even considering emissions from electricity production (likely grid-based), perform better in terms of carbon footprint. However, they still produce CO_2, due to grid energy sources still involving fossil fuels.

3. Hydrogen via Steam Methane Reforming (H_2 SMR): Hydrogen produced from natural gas (without carbon capture) reduces CO_2 emissions compared to diesel but still shows a considerable carbon footprint, due to the reliance on natural gas as the feedstock for hydrogen production.

4. Hydrogen via SMR with Carbon Capture (H_2 SMR + CCS): This approach significantly reduces emissions compared to standard SMR, but it is not completely carbon-neutral. The introduction of carbon capture and storage (CCS) technology helps lower the emissions.

5. Hydrogen via Grid Electrolysis (H_2 Grid Electrolysis): This method results in the highest CO_2 emissions among all hydrogen options, even surpassing diesel, indicating that hydrogen produced via grid-based electrolysis—largely reliant on fossil fuel-generated electricity—can be highly carbon-intensive.

6. Hydrogen via Solar Electrolysis (H_2 Solar Electrolysis): This option demonstrates the lowest CO_2 emissions, close to zero, showcasing the potential of using renewable energy like solar power to produce hydrogen with minimal environmental impact.

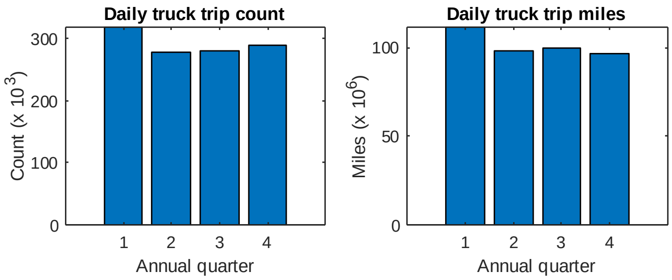


Figure 19. Daily trips and VMT (using FAF data)

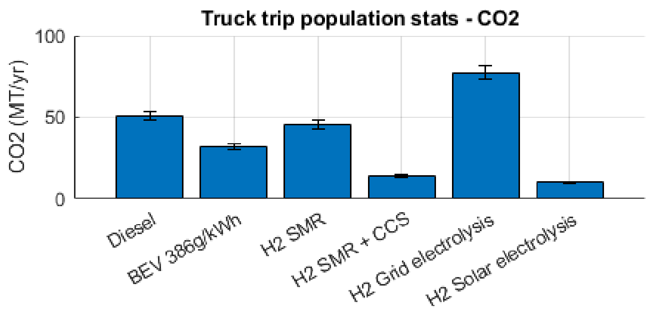


Figure 20. CO2 emissions impact based on different energy sources

Figure 21 compares the refueling or recharging rates of various truck propulsion systems in miles of range acquired per minute of refueling or recharging. Key observations include**:**

1. Diesel's Superior Refueling Speed: Diesel trucks refuel at a significantly faster rate (approximately 275 miles/min) compared to alternative powertrains. This highlights diesel's current dominance in terms of minimizing downtime for refueling, making it attractive for industries prioritizing efficiency and turnaround time.

2. BEV: BEVs with charging capacities ranging from 150 kW to 3750 kW exhibit progressively increasing refueling rates, but even the highest capacity chargers (3750 kW) reach only a fraction of diesel's range gain per minute recharging. The highest-rated BEV charger achieves around 40 miles per minute, showcasing the slower energy transfer rates for electric vehicles and the importance of faster charging solutions for commercial fleets.

3. Hydrogen Refueling Rates: Hydrogen refueling speeds are categorized by the flow rate of hydrogen (in kg/min), with higher range rates as the flow increases. Hydrogen refueling shows rates that can reach close to 100 miles/min at 10 kg/min, though still trailing behind diesel significantly. Nevertheless, hydrogen refueling outperforms electric vehicle charging in terms of miles per minute, especially at higher flow rates.

4. Comparison Between BEVs and Hydrogen: Hydrogen fuel cell vehicles (FCVs) demonstrate faster refueling rates than most BEV charging scenarios, especially at higher hydrogen flow rates. This suggests that hydrogen may present a more competitive refueling solution for long-haul trucks or applications where minimizing downtime is critical.

5. BEV Charging Capacity Matters: The refueling rate increases significantly with the higher charging capacities for BEVs (e.g., from 150 kW to 3750 kW), showing the impact that investment in higher power charging infrastructure can have. However, even at the highest BEV charging rates, diesel and hydrogen (at higher flow rates) maintain a clear advantage.

6. Diesel remains the fastest option, but as the industry shifts toward zero-emission vehicles, hydrogen emerges as a more viable option for long-haul and time-sensitive applications due to its relatively fast refueling rates compared to BEVs. Battery electric vehicles, while offering environmental benefits, still face limitations in refueling speed, which could hinder their adoption for long-distance commercial operations unless ultra-fast charging infrastructure becomes more widespread and efficient.

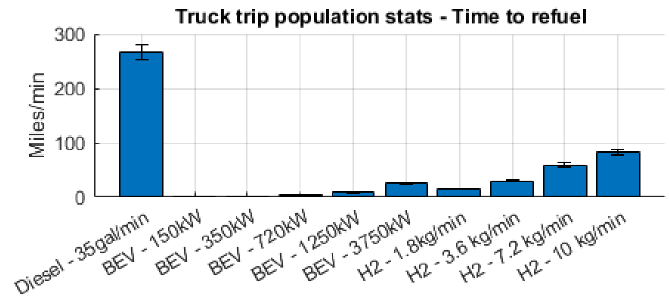


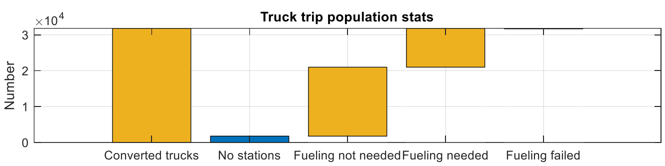
Figure 21. Refueling time impact based on different energy sources

In the following analysis for both ***hydrogen fueling station siting*** and ***electric charging station siting***, we assume a 10% conversion of truck trips from diesel to zero-emission powertrains (lacking other targets this is motivated by CARB ACF regulations). These results can be scaled based on higher or lower adoption rates. However, certain non-linear effects, such as the number of dispensers or chargers and the corresponding peak power demand, are expected to vary according to the adoption profiles. Additionally, roadmapping for preferred adoption scenarios is illustrated, though not fully developed in this paper, based on the amount of infrastructure deployed. This highlights the importance of strategic planning for both hydrogen and electric vehicle infrastructure to meet future adoption demands.

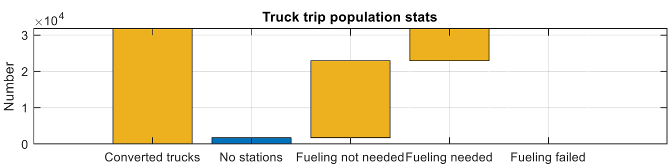
B. Hydrogen Fuel Station Siting

Figure 22 illustrates the number of truck trips converted to hydrogen power, highlighting both trips that require refueling and those that can complete the journey without refueling. The optimization metrics previously discussed are applied to ensure that no vehicles are stranded due to fuel shortages, which is confirmed by the data shown in Figure 22. Additionally, we observe that the size of the hydrogen storage tank significantly affects the need for refueling during trips. Larger tanks reduce the frequency of refueling stops, while smaller tanks may require more frequent stops. As a result, the number and location of refueling stations are directly influenced by the vehicle's onboard hydrogen storage capacity, impacting the overall infrastructure planning for hydrogen-powered freight transport.

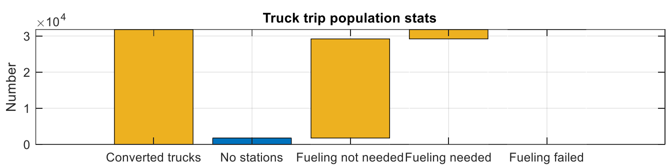
This optimal solution is achieved by strategically siting hydrogen refueling stations along the extended H2LA corridors, accounting for three different onboard hydrogen storage capacities: 70 kg, 80 kg, and 100 kg. These storage sizes represent typical 700-bar gaseous hydrogen tanks used in heavy-duty trucks, positioned behind the cab. By factoring in varying storage capacities, the stations are optimally located to ensure continuous operation of hydrogen-powered vehicles over long distances, minimizing the need for refueling stops while supporting the decarbonization of freight transport. Figure 23 illustrates the strategic placement of in-route hydrogen refueling stations to support long-distance travel for trucks equipped with these storage capacities. The locations of these stations are designed to align with the key routes shown in Figure 9, Figure 10, and Figure 11, ensuring continuous operation without exceeding the vehicle's fuel range limits. The map highlights critical nodes where hydrogen refueling infrastructure is essential for enabling the feasibility and reliability of hydrogen-powered heavy-duty trucks over vast interstate routes. This infrastructure ensures that hydrogen fuel cell trucks can perform long-haul operations, contributing to the decarbonization of freight transport. By providing refueling stations at pivotal locations, this setup supports the seamless integration of hydrogen technology into the logistics network while reducing emissions and maintaining operational efficiency across the supply chain. In these figures, the size of each circle represents the amount of hydrogen dispensed at each location, with more detailed data provided in Figure 24. Along with the in-route refueling points, each destination replenishes the truck's fuel to full capacity, ensuring readiness for the return trip or subsequent legs. This refueling activity is also depicted in Figure 24. Additionally, it is important to note that we assume each truck begins its trip with a full tank at the origin, and fuel levels are never allowed to drop below 20% capacity to maintain a reserve buffer, ensuring flexibility and avoiding potential fuel shortages. This accounts for the differences in sum of the total fuel dispensed in-route and at the destinations.



(a) Hydrogen storage capacity: 70kg



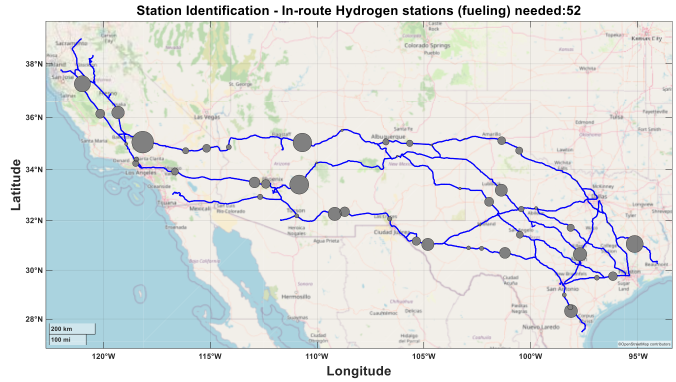
(b) Hydrogen storage capacity: 80kg



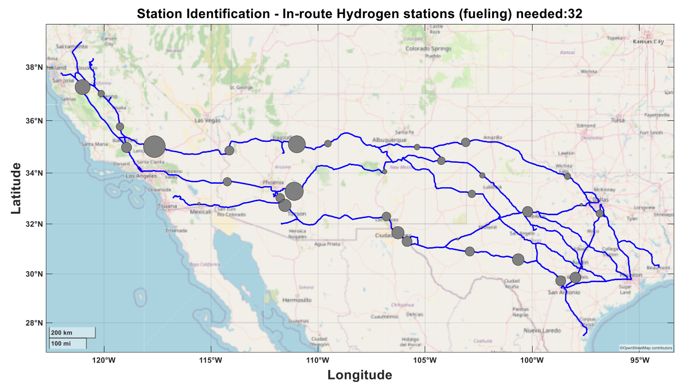
(c) Hydrogen storage capacity: 100kg

Figure 22. Truck trip population fueling statistics

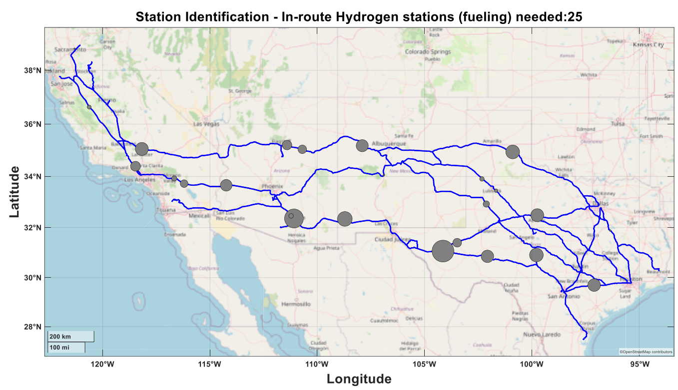
This strategic approach underscores the importance of hydrogen as a viable alternative to diesel for sustainable long-distance trucking.



(a) Hydrogen storage capacity: 70kg

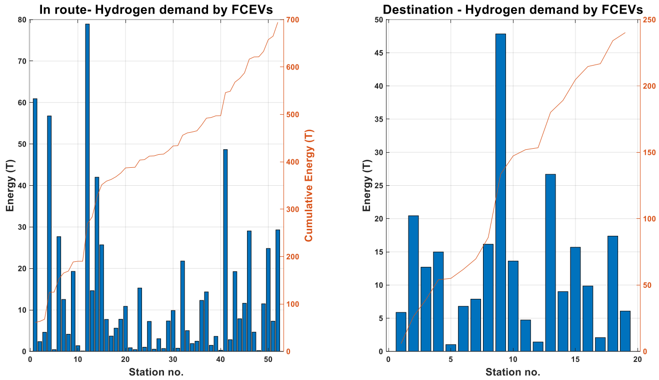


(b) Hydrogen storage capacity: 80kg

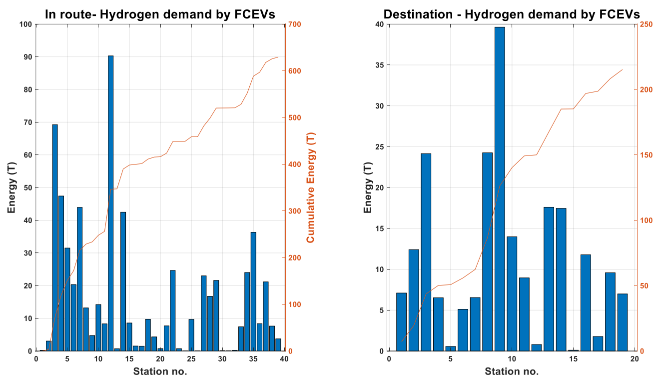


(c) Hydrogen storage capacity: 100kg

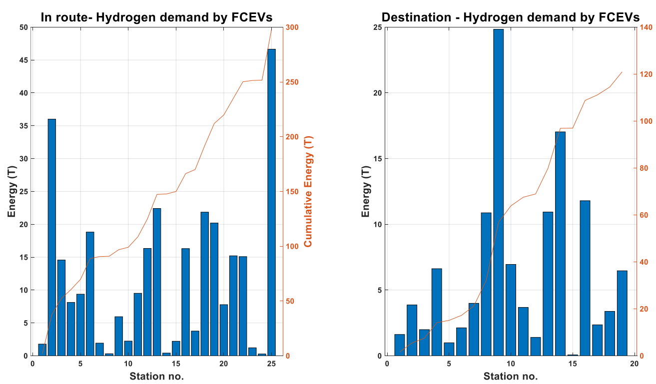
Figure 23. Station identification for 100% truck mission completion rate (circle size represents the amount of hydrogen dispensed)



(a) Hydrogen storage capacity: 70kg



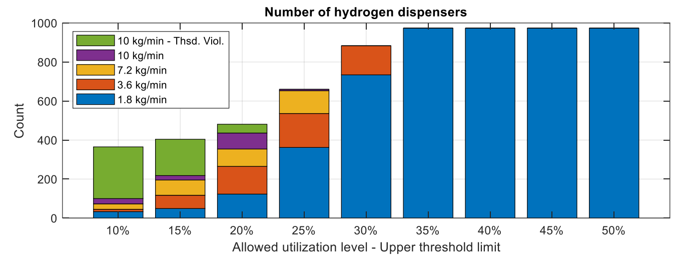
(b) Hydrogen storage capacity: 80kg



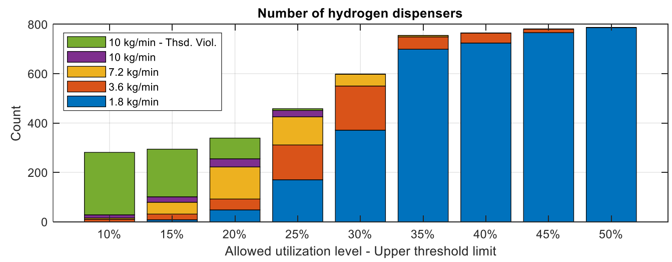
(c) Hydrogen storage capacity: 100kg

Figure 24. Hydrogen dispensed at each site (in-route / destination)

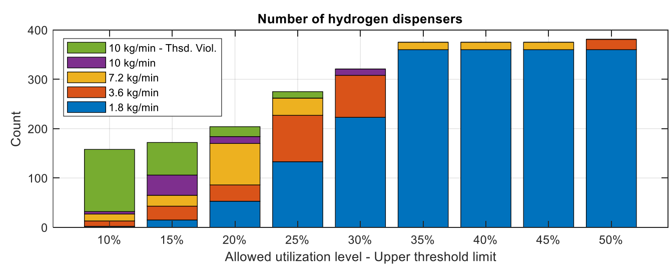
Figure 25 examines the impact of dispenser types and their associated utilization levels on hydrogen refueling infrastructure. Typical refueling stations aim to maintain an upper utilization limit to ensure dispenser availability when trucks arrive. This target utilization may vary depending on the service provider. For this study, we assume that each station operates with a single dispenser technology (ranging from 1.8 to 10 kg/min) and that all stations in the region target the same utilization level. By setting a uniform utilization target across all stations, we can estimate the number of dispensers of each type required for the region. Figure 25 illustrates this for all in-route refueling stations. As anticipated, larger tanks reduce the need for extensive infrastructure but increase vehicle capital costs. Conversely, smaller tanks demand more infrastructure and require more frequent refueling stops. Since infrastructure costs are typically passed on to the end-user through hydrogen pricing, vehicles with smaller tanks may incur higher operational expenses due to the need for additional refueling infrastructure. This trade-off between tank size, infrastructure requirements, and overall costs underscores the need for further analysis using OR-AGENT to optimize solutions for hydrogen refueling infrastructure development. This ongoing study will help determine the best balance between capital and operational expenses to ensure cost-effective, scalable solutions for the hydrogen trucking ecosystem.



(a) Hydrogen storage capacity: 70kg



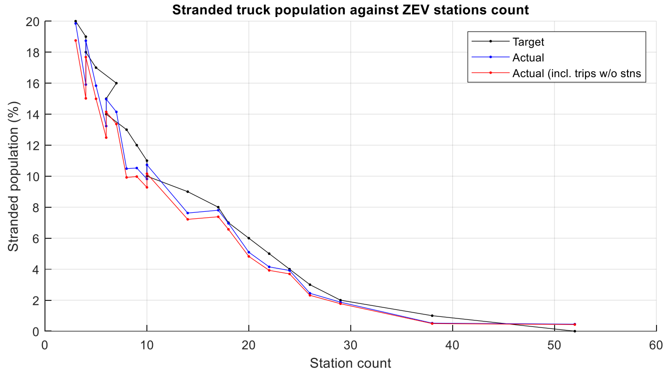
(b) Hydrogen storage capacity: 80kg



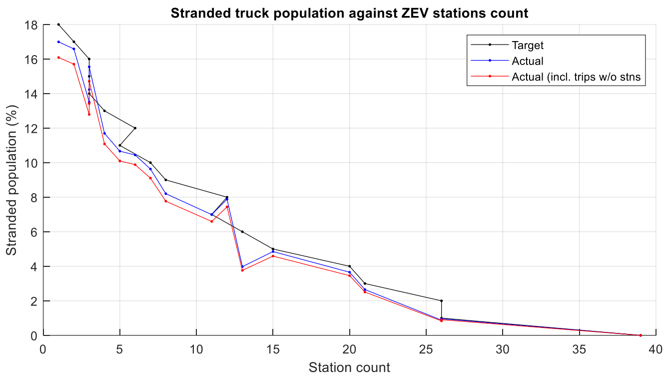
(c) Hydrogen storage capacity: 100kg

Figure 25. Dispenser type count 100% truck mission completion rate

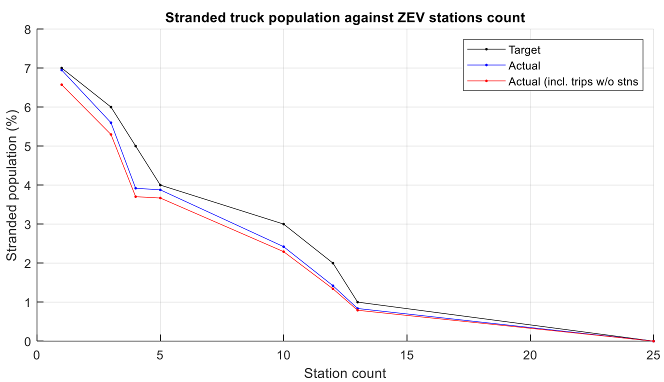
In Figure 26, we evaluate the impact of reducing the number of hydrogen refueling stations on the percentage of truck trips that become unviable. Initially, 10% of truck trips were randomly selected for conversion to hydrogen powertrains. However, as the number of refueling stations decreases, the percentage of successful trips also declines, with specific trips being eliminated from feasibility rather than random ones. Figure 26 highlights this relationship, showing how a reduced station deployment directly affects the proportion of trips within the initial 10% population that are no longer feasible for hydrogen conversion. This analysis allows for targeted optimization, where, based on a set number of stations, a specific subset of truck trips can be strategically chosen for hydrogen powertrain conversion. This approach ensures that infrastructure limitations are considered in future deployment strategies.



(a) Hydrogen storage capacity: 70kg



(b) Hydrogen storage capacity: 80kg



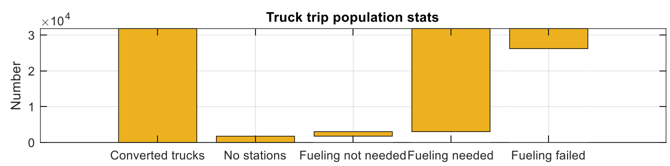
(c) Hydrogen storage capacity: 100kg

Figure 26. Station quantity based on truck mission completion rate

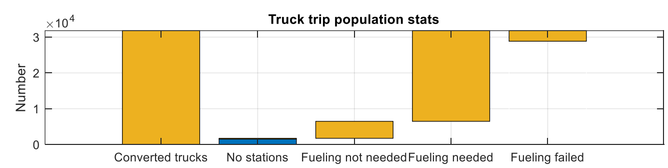
C. Electric Charging Station Siting

A parallel analysis is conducted for BEVs, focusing on battery capacities ranging from 438 kWh to 1000 kWh, which represent current market technologies such as those seen in the Freightliner eCascadia[5], Nikola Tre BEV[6], and the SuperTruck III program[7]. For this study, the usable battery capacity is set at 80%, reflecting standard operational practices to extend battery life and account for efficiency losses. Additionally, vehicles are programmed to initiate a recharge event when the state of charge (SOC) falls below 15%, creating a buffer to accommodate unforeseen events, such as unexpected delays or detours. This ensures that the vehicle will not face a critical shortage of power during operation. The following figures illustrate the outcomes of this BEV analysis, highlighting the implications of varying battery capacities and state of charge management on vehicle range, charging frequency, and overall operational efficiency. By maintaining these parameters, the study provides insights into the infrastructure needs and logistical considerations for supporting BEV fleets in long-haul operations, while also accounting for the safety and flexibility required in real-world scenarios.

The analysis highlights several critical observations regarding BEVs compared to hydrogen FCEVs in the context of long-haul truck trips. First, as seen in Figure 27, even with the deployment of multiple charging stations, all three battery sizes result in stranded vehicles for part of the population. This indicates that no matter how many stations are selected from the candidate sites, some trucks will not complete their routes without encountering range issues. Additionally, Figure 28 illustrates that BEVs require significantly more charging stations compared to hydrogen refueling stations for the same population of vehicles. While the overall energy dispensed for BEVs may be slightly lower than for hydrogen, as shown in Figure 29, this is offset by the higher efficiency of BEV powertrains. However, a new challenge emerges with the power needed to support BEV charging, given the wide range of charger power levels from 150kW to 1250kW (Figure 30). The substantial infrastructure demands, including the number of chargers and charging spots, further complicate this situation. Lastly, Figure 31 presents the percentage of stranded vehicle trips, clearly showing that even with a high number of charging stations, a significant portion of the population remains stranded. This underscores the complexity of electrifying long-haul freight using BEVs and highlights the critical need for optimized infrastructure to ensure that these vehicles can complete their missions without interruptions.



(a) Battery storage capacity: 438kWh



(b) Battery storage capacity: 733kWh

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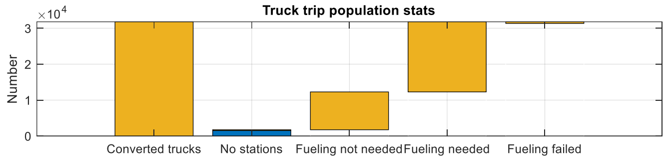
[5] Freightliner eCascadia: https://www.freightliner.com/trucks/ecascadia/)

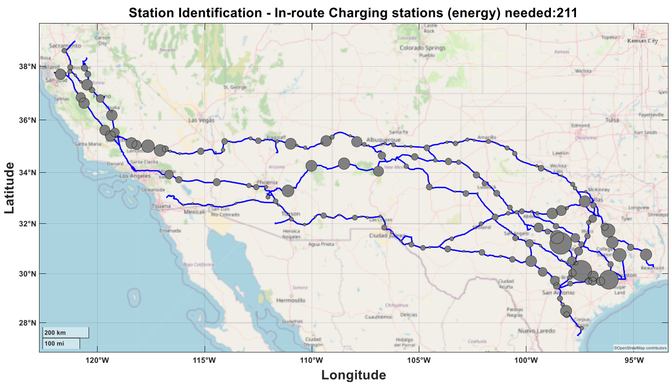
[6] Nikola Tre BEV: https://www.nikolamotor.com/tre-bev

[7] SuperTruck III program: https://www.energy.gov/articles/doe-announces-162-million-decarbonize-cars-and-trucks

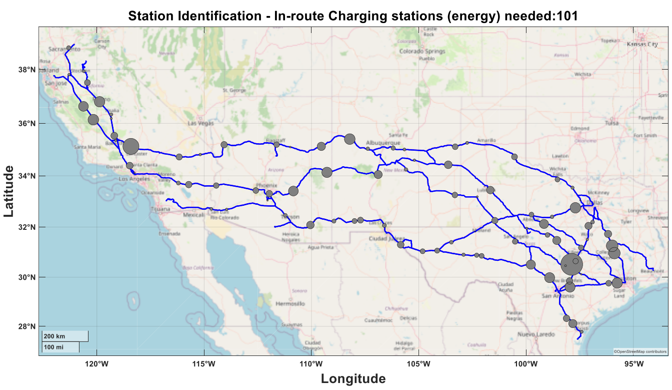


(c) Battery storage capacity: 1000kWh

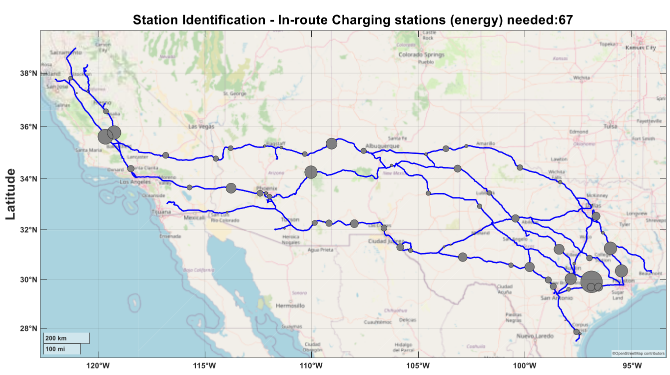
Figure 27. Truck trip population charging statistics



(a) Battery storage capacity: 438kWh

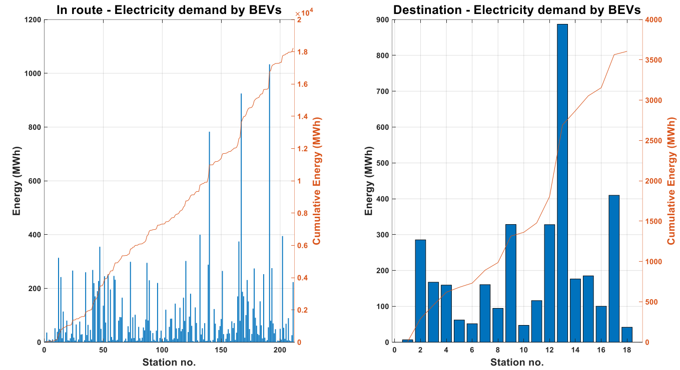


(b) Battery storage capacity: 733kWh

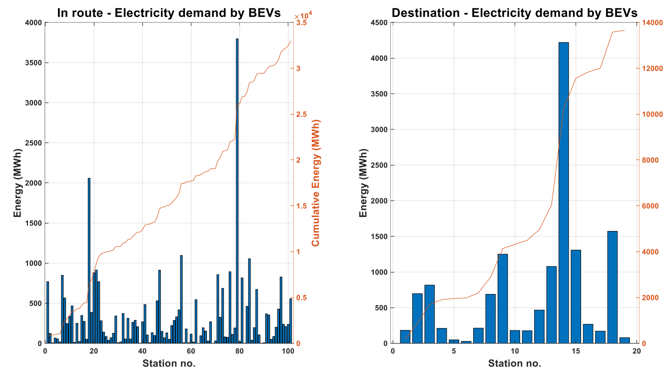


(c) Battery storage capacity: 1000kWh

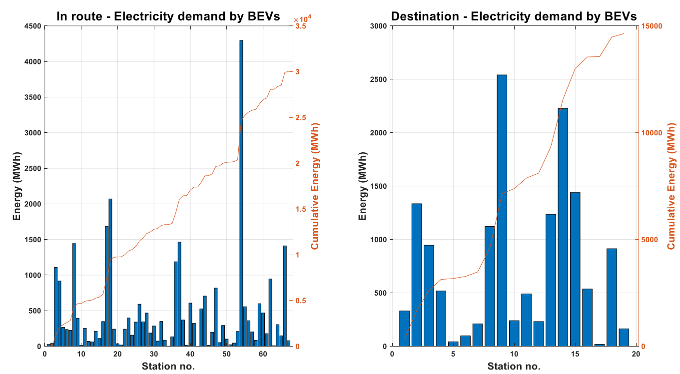
Figure 28. Station identification for maximum truck mission completion rate (circle size represents the amount of electricity dispensed)



(a) Battery storage capacity: 438kWh

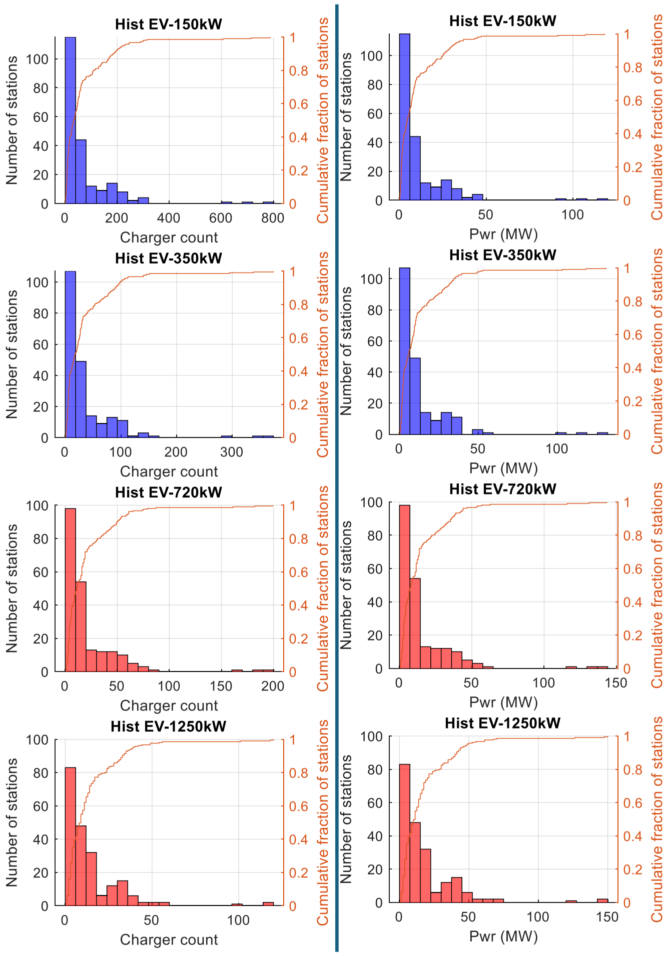


(b) Battery storage capacity: 733kWh

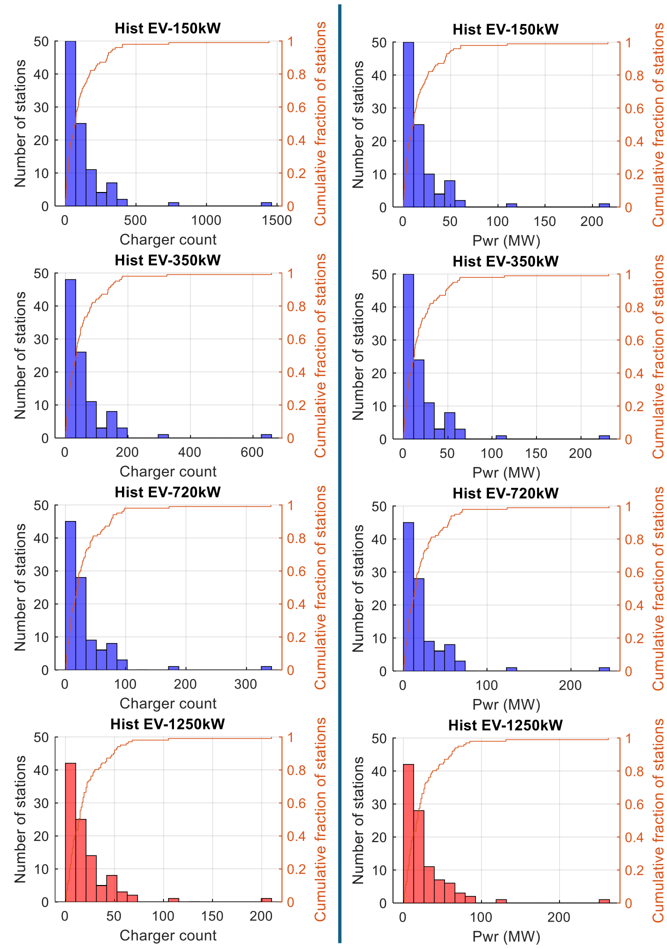


(c) Battery storage capacity: 1000kWh

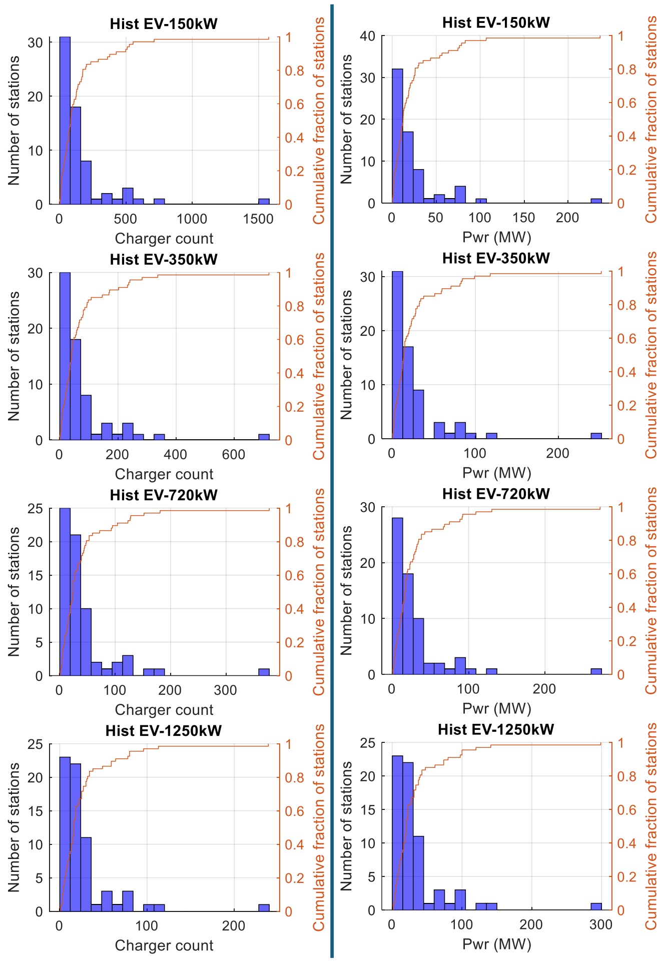
Figure 29. Electricity dispensed at each site (in-route / destination)



(a) Battery storage capacity: 438kWh

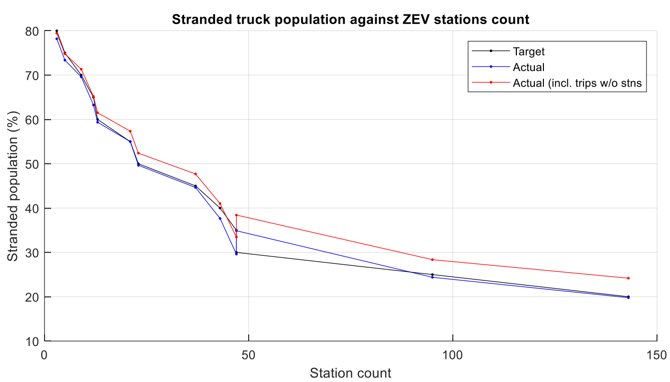


(b) Battery storage capacity: 733kWh

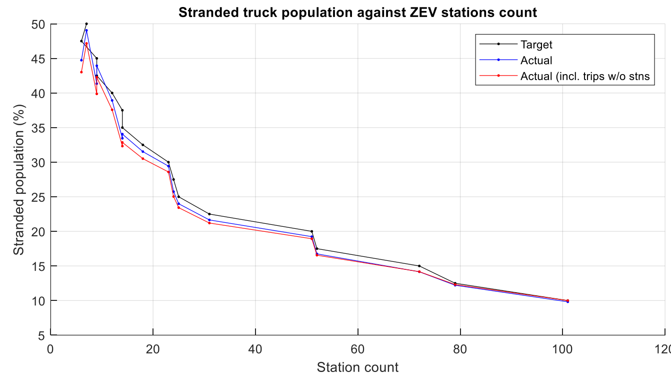


(c) Battery storage capacity: 1000kWh

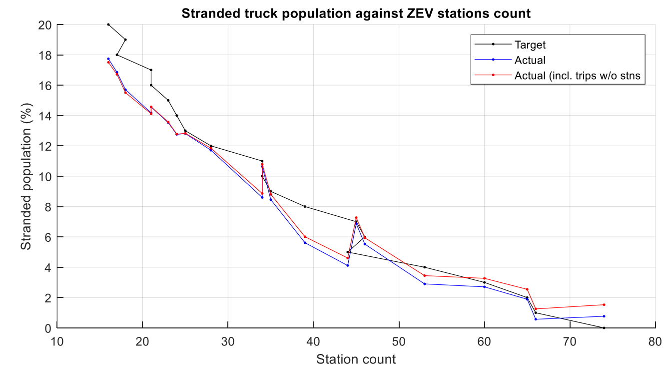
Figure 30. Charging power statistics at each site (in-route). Red indicates charging power may exceed 1.5C.



(a) Battery storage capacity: 438kWh



(b) Battery storage capacity: 730kWh



(c) Battery storage capacity: 1000kWh

Figure 31. Station quantity based on truck mission completion rate

Discussion

This paper focuses on infrastructure siting and well-to-wheel emissions, but it's important to note the distinct lifecycle carbon impacts of BEVs and FCEVs. BEVs have significant lifecycle emissions due to the resource-intensive battery manufacturing and end-of-life processes. In contrast, FCEVs' lifecycle emissions depend heavily on the energy-intensive production of the fuel cell stack, including the mining and processing of materials like platinum. Ultimately, the choice between BEVs, FCEVs, or other powertrain technologies for decarbonizing heavy-duty trucking will depend on advancements in energy sourcing, infrastructure, and technology to reduce lifecycle emissions across all pathways.

The above analysis shows BEVs and hydrogen FCEVs both offer promising pathways for the well-to-wheel decarbonizing of heavy-duty trucking, but each comes with distinct advantages and challenges. BEVs benefit from higher overall powertrain efficiency and lower operational costs, as electricity is generally cheaper than hydrogen. They also have a more established charging infrastructure, particularly for light and medium-duty vehicles. However, BEVs face significant drawbacks in heavy-duty applications, including long charging times, the need for high-power chargers (150kW to 1250kW), and range limitations, especially over long-haul routes. Additionally, BEV trucks require a larger number of charging stations to avoid "stranded" vehicles, which can be challenging due to the high-power demands and associated infrastructure costs.

In contrast, FCEVs can refuel much faster and offer longer ranges, making them more suitable for long-distance trucking. They also require fewer refueling stations compared to BEVs, reducing the overall infrastructure burden. However, FCEVs face challenges with the current hydrogen production, distribution infrastructure, and higher fuel costs. The carbon intensity of hydrogen production, particularly from fossil fuels, also raises concerns about the overall environmental impact unless green hydrogen production is scaled up. Ultimately, the choice between BEV and FCEV heavy-duty trucks depends on factors like route length, infrastructure availability, and cost considerations.

In addition to establishing siting needs setting up a new multi-megawatt (MW) charging station for electric vehicles (BEVs), or hydrogen refueling stations for fuel cell electric vehicles particularly for commercial fleets and heavy-duty vehicles, requires careful consideration of various technical, operational, and environmental factors. While beyond the scope of analysis of this paper it is noteworthy to highlight these key considerations which include:

A. Location and Accessibility

The site for a multi-megawatt charging or refueling station should be strategically located along major freight corridors for easy access by commercial vehicles. Traffic volume and demand forecasting are crucial to prevent congestion. The station must provide ample space for large vehicles, parking, maneuvering, hydrogen storage, electrical equipment, safety buffers, and communications infrastructure for smart grid and monitoring systems.

B. Energy Supply and Infrastructure

For multi-megawatt charging stations, it is crucial to assess the local grid's capacity to handle high electrical loads, potentially requiring coordination with utility companies for infrastructure upgrades or direct substation connections. Incorporating energy storage systems can help balance the grid load and provide backup power. Managing demand charges from utilities and implementing smart charging strategies to distribute power effectively are key for minimizing costs and reducing peak loads.

Hydrogen refueling stations must ensure reliable access to clean hydrogen with adequate on-site storage, possibly requiring proximity to production facilities. Green hydrogen, produced through electrolysis powered by renewable electricity, offers a good solution but requires significant infrastructure investment, including renewable energy generation and electrolysis plants. Blue hydrogen, made via steam methane reforming with carbon capture and storage (CCS), also faces high costs due to the expensive nature of CCS technology. Both involve substantial infrastructure development and costs, with their economic feasibility relying on advancements in technology, scaling, and policy support to reduce expenses.

C. Refueling/Charging Technology and Capacity

Multi-megawatt stations for commercial vehicles must provide ultra-fast charging (e.g., 350 kW or higher) using high-power DC chargers to minimize downtime. Hydrogen refueling stations need to be equipped with high-pressure (350 bar or 700 bar) or liquid dispensers for safe and rapid refueling of fuel cell electric vehicles (FCEVs). The layout of chargers/dispensers and the number of required bays should optimize traffic flow and reduce vehicle wait times.

D. Safety and Regulatory Compliance

Hydrogen refueling stations must adhere to strict safety standards for the storage and handling of hydrogen, including measures like leak detection, fire suppression, and emergency shutdown systems. BEV charging stations must also comply with electrical safety regulations. Additionally, the infrastructure must be protected from cybersecurity threats, and physical security measures should be in place to prevent vandalism or theft, especially at remote locations.

E. Environmental Considerations

To minimize the carbon footprint, charging stations should be powered by renewable energy sources like solar or wind, or offer green hydrogen produced via electrolysis using renewable energy. Additionally, the impact on the electrical grid should be assessed, especially for multi-MW BEV charging stations, with energy management strategies such as demand response implemented to mitigate potential strain.

F. Economic Viability

Initial capital and operational costs, including infrastructure, grid upgrades, hydrogen supply, electricity rates, and maintenance, must be carefully considered. A robust business model should also factor in potential revenue from energy sales, public-private partnerships, and government incentives. Additionally, reducing vehicle pricing, particularly by lowering battery costs for both BEVs and FCEVs, is crucial for making these technologies more economically viable.

G. Scalability and Future-Proofing

The station should be designed with future expansion in mind to accommodate growing demand and integrate advancements in both charging and hydrogen technologies, ensuring it can support higher power levels or more efficient refueling processes. Clean grid electricity will play a critical role in powering both BEV charging and electrolytic hydrogen production. Consequently, grid expansion will be essential for supporting both battery electric and hydrogen trucks, making it a key consideration for the development of infrastructure for both technologies.

H. User Experience and Convenience

To minimize downtime for commercial fleets, charging stations should provide fast charging and hydrogen refueling. Essential amenities like restrooms, food, and overnight parking should be available, especially for long-haul drivers. Real-time monitoring software should track charger performance, availability, and energy usage, while reliable payment systems should support various methods, including credit cards, RFID, and mobile apps.

Conclusion

This study underscores the complex but essential task of decarbonizing regional and long-haul freight, given the limitations of BEVs and the infrastructure demands of hydrogen FCEVs. Through a comprehensive analysis using the OR-AGENT framework, the research demonstrates that both BEVs and FCEVs offer viable pathways for decarbonization, but each comes with distinct advantages and challenges.

FCEVs, particularly MHDVs, align well with decarbonization goals set by the Department of Energy and commercial entities. The study highlights that hydrogen-powered trucks have the potential to meet the energy demands of long-haul freight with fewer refueling stations due to their extended range capabilities. However, the carbon intensity of hydrogen production, especially when sourced from fossil fuels, presents a significant challenge. Therefore, the successful deployment of zero-emission hydrogen refueling infrastructure will depend on integrating cleaner production methods, such as renewable or low-carbon hydrogen, to fully realize the environmental benefits. Furthermore, by strategically placing hydrogen refueling stations, the infrastructure can be rolled out affordably and efficiently, with a particular focus on underserved and rural communities that could see improvements in air quality, noise pollution, and energy resiliency.

In contrast, BEVs present a different set of challenges. While they boast higher powertrain efficiency, their limited range and high demand for charging infrastructure—particularly fast chargers—make them less suitable for long-haul freight without significant grid upgrades. The study found that even with a higher density of charging stations, a considerable number of BEV trips were left stranded, which indicates a need for further optimization in charging station deployment and grid capacity. Additionally, the high-power demands for BEV charging infrastructure (due to the concurrent use of multiple chargers ranging from 150kW to 1250kW), exacerbate the strain on the grid, complicating their broader deployment for long-haul operations.

The research primarily focuses on key freight corridors in the Texas Triangle Megaregion (I-45, I-35, and I-10), as well as the I-10 corridor between San Antonio, TX, and Los Angeles, CA, and the I-5/CA-99 corridors in California. These routes are crucial for U.S. freight movement. By using the OR-AGENT framework, the study identifies optimal locations for hydrogen refueling stations and FCEV refueling or BEV charging stations, with the objective of minimizing the number of vehicles stranded along these high-volume freight corridors. Additionally, it offers a first view roadmap for hydrogen refueling station deployment based on different adoption trajectories, aiming for a strategic and scalable rollout.

Future work will focus on:

- Quantified roadmap for hydrogen or BEV station and prioritized truck route conversion
- Optimum distribution of combining of both BEV and FCEV technologies which may be necessary to meet the diverse needs of the heavy-duty trucking sector. While BEVs are better suited for shorter, regional hauls due to their efficiency, FCEVs show more promise for long-haul applications, particularly if hydrogen production is decarbonized.

This dual approach can support the transition to a zero-emission freight system, reducing greenhouse gas emissions, improving air quality, and enhancing energy resiliency, especially for rural and energy-stressed communities. Effective infrastructure planning and deployment are critical to overcoming the challenges seen with alternative fuels in the past and ensuring the success of decarbonization efforts in commercial freight transport.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy's Office (DOE) of Energy Efficiency and Renewable Energy (EERE) under the Vehicle Technologies Office (VTO) Fiscal Year 2022 Vehicle Technologies Office Program Wide Funding Opportunity Announcement Award Number DE-EE0010650. The authors would also like to acknowledge Ben Gould / Jesse Adams (DOE), Bart Sowa (GTI), Dr. Emily Beagle / Michael Lewis / Lea Daniel, (University of Texas, Austin), Chris Gurciullo / Cate Kehn (ExxonMobil), Hank Murphy / Marco Ugarte / Ben Whitmore (Walmart) for their ongoing support of this research project.

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Definitions/Abbreviations

BA	**Balancing Authorities**
BEV	**Battery Electric Vehicle**
CH4	**Methane**
CO2	**Carbon Dioxide**
CV	**Commercial Vehicles**
DER	**Distributed Energy Resources**
DOE	**Department of Energy**
DOT	**Department of Transportation**
EEJ	**Environmental Equity and Justice**
EIA	**Energy Information Administration**
EPA	**Environment Protection Agency**
FAF	**Freight Analysis Framework**
FCEV	**Fuel Cell Electric Vehicle**
FHWA	**Federal Highway Administration**
GA	**Genetic Algorithm**
GHG	**Greenhouse Gas**
GIS	**Geographic Information Systems**
GPS	**Global Positioning System**
H2Hubs	**Hydrogen Hubs**
H2LA	**Houston to Los Angeles**
HVAC	**Heating, Ventilation, Air conditioning**
ICE	**Internal Combustion Engine**
IIJA	**Infrastructure Investment and Jobs Act**
Kg	**Kilogram**
kW	**Kilowatt**
kWh	**Kilowatt-hour**
LCOE	**Levelized Cost of Energy**
MHDV	**Medium and Heavy-Duty Vehicles**
MILP	**Mixed Integer Linear Programming**
MW	**Megawatt**
N2O	**Nitrous Oxide**

NAERM	**North American Energy Resilience Model**
NEVI	**National Electric Vehicle Infrastructure**
NHTS	**National Household Travel Survey**
NOAA	**National Oceanic and Atmospheric Administration**
NSRDB	**National Solar Radiation Database**
NZEV	**Near Zero Emission Vehicle**
OD	**Origin-Destination**
ODC	**Operating Domain Characterization**
ODS	**Operating Domain Specification**
OR-AGENT	**Optimal Regional Architecture Generation for Electrified National Transport**
OR-SAGE	**Oak Ridge Siting Analysis for Power Generation**
ORNL	**Oak Ridge National Laboratory**
reV	**Renewable Energy Potential**
SCM	**Smart Charge Management**
TCO	**Total Cost of Ownership**
TEU	**Twenty-foot Equivalent Unit**
UTC	**Coordinated Universal Time**
V2G	**Vehicle to Grid**
V2H	**Vehicle to Home**
VMT	**Vehicle Miles Traveled**
WIM	**Weigh in Motion**
WIND	**Wind Integration National Dataset**
ZEV	**Zero Emission Vehicle**

Appendix A

Reviewer #1: Comments and response

1. the introduction section is too long, and the authors take too long to get to the point of why this study is needed. This also makes the manuscript too lengthy. My suggestion is to reduce some of the figures that are not needed to be stressed (e.g., Figures 2 and 3) and summarize the paragraphs on H2Hubs and NEVI program in a single paragraph. This way, things can be kept more succinct and crisp. I would instead, suggest adding an appendix section in the end where some of these details can be added. I would also suggest applying this suggestion to reduce the text count of the manuscript with transfer of more content in the appendix. Also, the manuscript name must be changed to reflect both hydrogen infrastructure and electrification-related aspects.

   We have rebuilt the introduction to be more to the point and added some additional relevant background work to tie-in with these comments and the comments of reviewer #2.

   Introduction has also been reduced substantially. We have removed figures 2 and 3 as this can be considered as superfluous to this work but the references are provided.

   H2Hubs and NEVI discussion has been reduced to a single paragraph as suggested.

   We have reduced quite a bit of text in the remaining part of the document.

   Name change introduced to account for both hydrogen and electric vehicles

2. while the authors have presented well-to-wheel analysis and that is important, a more comprehensive picture is provided by life-cycle analysis to understand the environmental impacts of different technologies like transport vehicles. My suggestion is that the authors at least mention this aspect in the manuscript in a brief manner.

   This is a good point and has been brought up in the introduction and discussions section to make the point and relevance of the paper clear. It is notes that lifecycle emissions across these and other powertrains must be considered and decisions on well-to-wheel or tank-to-wheel must not be made in isolation.

3. hydrogen production, and more specifically, the method used for hydrogen production. In the discussion sector, the authors highlight the importance of energy storage systems, grid capacity, and building hydrogen supply chain for energy supply and infrastructure (Section B). However, the authors do not mention that any kind of green technology use for hydrogen production (be it carbon capture and storage with steam methane reforming, or electrolysis using grid-based or renewable electricity) will involve significant amount of new infrastructure building/construction along with associated costs. Also, carbon capture and storage, at least per current cost estimates, will be significantly expensive, while battery energy storage will be relevant for both electric and hydrogen-fueled trucks and will also be expensive, while also adding to grid capacities/infrastructure (Section D has some of it but discussed very briefly). Grid expansion will therefore, be relevant for both battery electric and hydrogen trucks, and so should be carefully highlighted for both technologies. My suggestion is to expand on some of these things, while also summarizing the discussion to make it more succinct. One way to do so is to avoid sections like Section E (which does not seem to be that important and probably can be shortened to just 2-3 sentences). Again, a lot of points in this section seem generic and probably don't need to be highlighted in such extensive detail as has been done by the authors. A better thing would be to focus on specific aspects with regard to infrastructure deployment and leave out other things like amenities and payment systems or to summarize them in one sentence.

   These are all excellent comments. It's difficult to cover all these points without significant growth to the paper length. However, per your comments, we've added commentary to the discussion sections along with significant reduction in this section length.

Reviewer #2: Comments and response

4. Some statements are not correct. For example, BEV and hydrogen vehicles are not zero-emission vehicles if considering life cycle, and the amount of life cycle emissions highly depends on the power source. Please correct the statements whenever needed.

   Good point. This has been addressed in the introduction.

5. The paper provides a very informative introduction of the background of the study, yet has not explained in detail about the state-of-the-art regarding the fueling station deployment strategies, which would be valuable to identify the uniqueness and novelty of the proposed model compared to the existing efforts.

   Again, good point. We have added this in the introduction. The intent was to introduce this with the discussion on NEVI and BIL but was not completely clear.

6. It is quite unclear about the optimization process. Figure 20 is not completely understandable. Please give more details about the optimization methods used in each of the steps and how each of the steps interrelated, though this framework is introduced in ref[15].

   I have added some additional explanation but given the length of the paper this has been kept quite brief. The provided reference covers this in quite a bit more detail.

7. On page 11, why assume 10% conversion of truck trips from diesel to zero emission powertrain?

   Given the current lack of other targets, the 10% figure was selected primarily to align with CARB ACF regulations. While these standards do not apply uniformly across the entire study region, they provide a reasonable starting point for this analysis. Additionally, by accounting for the limited range of certain truck missions, it becomes feasible to conduct a robust prioritization study. This approach highlights the effects of station availability, as seen in the percentage of truck trips stranded when fewer stations are deployed. This methodology is being refined to illustrate the trade-offs involved in systematically prioritizing truck-trip conversions to hydrogen or battery-electric powertrains. Findings from this ongoing work will be presented in future publications. A note to this effect is added in the text.

8. To solve an optimization problem for such a big region requires a significant amount of computational resources. Can you describe the computational efficiency for generating one solution?

   The answer is not simple, as it depends on the available computational resources. Different steps of the process require varying amounts of time, with the largest computational burden associated with data integration for the <u>Operating Domain Characterization step</u>. This step can take multiple weeks, depending on the region's size and the resolution of the OD. After building the OD routes, <u>vehicle simulations step</u> for a region with approximately 300K routes per day typically take 1-2 weeks, even when running on multiple cores of a supercomputer network using low-resolution data (as shown in this paper). Once the data is integrated, generating the <u>smart energy management architecture step</u> for the flexible known points takes only 1-2 hours on a single desktop workstation to produce a solution. This step is usually set up to run multiple times under different conditions, minimizing the need for the slower data integration steps.

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