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Moving Towards the Electrification of Medium- and Heavy-Duty Vehicles in the Inland Empire

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Report 24-24

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16. Abstract

This report investigates the transition to zero-emission medium- and heavy-duty vehicles (MDHD) within California's Inland Empire (IE), emphasizing the significance of electric vehicle charging infrastructure and opportunity charging strategies in facilitating sustainable transportation. Utilizing a mixed-methods approach that combines a systematic literature review, geospatial and big data analytics, and thematic analysis of expert interviews, the study explores the multifaceted challenges and opportunities of electrification. The literature review assesses policies at various governance levels, while geospatial analysis identifies regional traffic patterns and infrastructure needs. Big data analytics examine vehicle movements, complemented by insights from interviews with 16 regional experts, offering a real-world perspective on the transition. The findings underscore the critical role of federal, state, and regional policies in supporting the shift towards zero-emission vehicles, highlighting the necessity for collaborative efforts to overcome infrastructural and financial challenges. The analysis reveals distinct operational patterns and infrastructure capacities across the IE's subregions, suggesting tailored electrification strategies to accommodate diverse needs. The study emphasizes the importance of equitable and economically viable approaches, particularly for small business stakeholders in the electrification process. Conclusively, the transition to MDHD EVs, while promising environmental and public health benefits, requires a nuanced, region-specific strategy that considers economic and infrastructural realities. Recommendations include adopting dynamic, adaptable policies, providing targeted financial incentives, standardizing charging technologies, and ensuring equitable benefits distribution. This comprehensive approach aims to balance technological advancements with supportive policies and equitable practices, facilitating a socially responsible and inclusive transition to sustainable transportation.

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List of Acronyms

AB	Assembly Bill
ACT	Advanced Clean Trucks
AMFA	Alternative Motor Fuels Act
AQMD	Air Quality Management District
AVFVTP	Alternative and Renewable Fuel and Vehicle Technology Program
BNSF	Burlington Northern Santa Fe Railway
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CAAQS	California Ambient Air Quality Standards
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CBRE	Coldwell Banker Richard Ellis
CCI	California Climate Investments
CCS	Carbon Capture and Storage
CEC	California Energy Commission
CFR	Code of Federal Regulations
CMAQ	Congestion Mitigation and Air Quality
COG	Council of Governments

CTF	California Transportation Foundation
CVRP	Clean Vehicle Rebate Project
DC	Direct Current
DERA	Diesel Emission Reduction Act
DOE	Department of Energy
DOT	Department of Transportation
EO	Executive Order
EPA	Environmental Protection Agency
EPCA	Energy Policy and Conservation Act
EPRI	Electric Power Research Institute
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
EVI	Electric Vehicle Infrastructure
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation
FCEV	Fuel Cell Electric Vehicle
FHWA	Federal Highway Administration
FTZ	Foreign Trade Zone
FY	Fiscal Year
GHG	Greenhouse Gas

GIS	Geographic Information Systems
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
GW	Gigawatt
HCD	Housing and Community Development
HD	Heavy-Duty
HDV	Heavy-Duty Vehicle
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICT	Information and Communications Technology
IE	Inland Empire
IRA	Inflation Reduction Act
ISR	Indirect Source Rule
ISTEA	Intermodal Surface Transportation Efficiency Act
IVDA	Inland Valley Development Agency
J1772	SAE J1772 (Electric Vehicle Charging Standard)
J3271	SAE J3271 (Megawatt Charging System)
JETSI	Joint Electric Truck Scaling Initiative
LCFS	Low-Carbon Fuel Standard
LH	Long-Haul
LMFP	Lithium Metal Fluoride Phosphate

LU	Land Use
MCS	Motor Carrier Safety
MD	Medium-Duty
MDHD	Medium- and Heavy-Duty
MDHD EV	Medium- and Heavy-Duty Electric Vehicle
MDHDV	Medium- and Heavy-Duty Vehicle
MDV	Medium-Duty Vehicle
MOU	Memorandum of Understanding
MPO	Metropolitan Planning Organization
MSRC	Mobile Source Air Pollution Reduction Review Committee
MW	Megawatt
NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System
NC	Noise Control
NFI	New Flyer Industries
NHTSA	National Highway Traffic Safety Administration
NO_x	Nitrogen Oxide
NREL	National Renewable Energy Laboratory
PHFS	Primary Highway Freight System
PIN	Personal Identification Number

PM	Particulate Matter
RFID	Radio-Frequency Identification
RMI	Rocky Mountain Institute
ROI	Return on Investment
RTP	Regional Transportation Plan
SAFETEA	Safe, Accountable, Flexible, Efficient Transportation Equity Act
SB	Senate Bill
SBCOG	San Bernardino County Transportation Authority
SBCTA	San Bernardino County Transportation Authority
SBIAA	San Bernardino International Airport Authority
SCAG	Southern California Association of Governments
SCE	Southern California Edison
SIP	State Implementation Plan
TCEP	Trade Corridor Enhancement Program
TCO	Total Cost of Ownership
TEA	Transportation Equity Act
TEU	Twenty-foot Equivalent Unit
TRU	Transport Refrigeration Unit
TRUC	Truck and Bus Regulation
TRUCRS	Truck Regulation Upload, Compliance, and Reporting System

TTGHG	Total Tailpipe Greenhouse Gas
V2G	Vehicle-to-Grid
VIP	Voucher Incentive Program
VVTA	Victor Valley Transit Authority
WAIRE	Warehouse Actions and Investments to Reduce Emissions
WRCOG	Western Riverside Council of Governments
ZE	Zero Emissions
ZEB	Zero-Emission Bus
ZETI	Zero Emission Truck Infrastructure
ZEV	Zero-Emission Vehicle

Executive Summary

This report, prepared for policymakers, industry stakeholders, environmental organizations, private and public transportation entities, presents a comprehensive analysis of the transition to zero-emission medium- and heavy-duty vehicles (MDHDVs) in California's Inland Empire (IE). It emphasizes the importance of this shift towards sustainable transportation and its significant role in global warming and GHG emissions mitigation, ultimately underscoring the practical benefits and potential impacts for all parties involved. The IE, including San Bernardino, Riverside Counties, and parts of eastern Los Angeles County, is a significant U.S. logistics hub and both public and private stakeholders are key players in this transition. This report explores challenges in electrifying MDHD fleets, focusing on battery technology, smart management systems, and charging infrastructure development. This report also examines environmental benefits, emission reductions, and explores economic implications, transportation planning, and the impact on access to electrification for both small independent operators and larger firms. Additionally, it considers potential negative consequences of this transition, ensuring a thorough and balanced overview of both the opportunities and challenges involved.

A normative analysis using a mixed-methods approach is conducted, combining a systematic literature review, geospatial and big data analytics, and a thematic analysis of expert interviews. This approach critically examines policies at the federal, state, and regional levels, with a focus on zero-emission vehicle (ZEV) transitions, energy regimes, and implications for smaller businesses. Spatial analysis of the IE's 27,000 square miles into six subregions is conducted using ArcGIS Pro, coupled with big data analytics for traffic and infrastructure analysis. Interviews with 16 regional experts, including those from government and business sectors, provide real-world insights.

The main questions of this research investigate current federal and state policies related to ZEV MDHD and identifies potential policy-related needs to facilitate the transition to a ZEV system. The research also delves into the current traffic patterns, volume, and origin-destination trends of MDHD vehicles in the IE, assessing locations for parking, resting, refueling, and examining logistics and distribution centers' characteristics. It also evaluates the total fleet size by owner type and explores potential sites and alternatives for EV charging infrastructure development. The last part of this report explores the impact of the EV infrastructure buildout and MDHD EV transition on low-income and disadvantaged residents in the IE, analyzes how these changes overlap with regional demographic and environmental justice maps, and considers equity in the implementation of EV technology.

The federal and state governments' role in facilitating this transition through policies, funding, and incentives is evaluated, along with the effects on different market segments and the workforce. This report analyzes the IE's logistics infrastructure, including its proximity to major ports and extensive freeway network, providing a comprehensive view of the region's potential for transformation into a sustainable, zero-emission MDHD fleet region. To ensure a thorough understanding, the analysis also sketches out scenarios during the mid-transition phase, where fleets will likely exhibit lower but still persistent emissions, highlighting the gradual shift towards fully zero-emission operations. The transition to ZEVs in the U.S., particularly in the IE, is supported by extensive federal, state, and regional actions. Federal initiatives, the Clean Air Act and Executive Orders lay the foundation for environmental and transportation reforms. California, with the passage of AB32 in 2006, has led this trend with legislation directing state agencies toward emission reduction targets and ZEV market development. Regionally, organizations implement local initiatives to integrate ZEVs into transportation infrastructure. Utility companies support this transition through infrastructure development programs. Collectively, these efforts underscore an important role that governmental actions play in not only shaping policy and economic landscapes but also in driving the practical implementations that will lead to a cleaner, sustainable future for the IE.

This report stresses the need for a tailored approach to electrification, considering the unique dynamics, economic frameworks, and infrastructure requirements of each IE subregion. It delves into the distinct needs and capacities of each subregion, aligning the electric MDHDV transition with broader sustainability goals. Varying operational patterns and infrastructure capacities across subregions are identified, with depot charging emerging as suitable for regions with high dwell times for HDVs, and opportunity charging beneficial for MDVs engaged in dynamic regional delivery services. Differences in grid transmission capacities and power plant capacities are also highlighted, influencing the electrification approaches advisable for various industry players, including fleet operators and regional planners. These tailored strategies ensure that the transition to EVs is both practical and sustainable, meeting the specific needs of each subregion within the IE.

Businesses, particularly independent owners and branch operations, are identified as primary stakeholders in the EV transition. This report emphasizes the need for equitable, economically viable electrification strategies that minimally disrupt these stakeholders. The multifaceted nature of MDHDV electrification, involving vehicular activity, economic considerations, and charging infrastructure is underscored.

The transition to MDHD EVs requires a region-specific approach, balancing environmental improvements with economic sustainability and equitable access. This calls for strategic collaboration among governments, businesses, and communities. Recommendations include dynamic, adaptable policies, targeted financial incentives for smaller businesses, standardization of charging technologies, and significant investment in infrastructure, particularly for opportunity charging. Ensuring equitable access to the benefits of electrification is paramount for a transition that is not only technologically advanced but also socially responsible and inclusive, particularly for communities that are economically disadvantaged or have historically lacked infrastructure investments. This focus helps ensure that all segments of society, especially those most vulnerable, can share in the advantages of a sustainable electrification strategy.

Part I: Introduction and Methods

1. Introduction

1.1 Background

California's transition to a zero-emission medium- and heavy-duty (MDHD) truck fleet is happening through the engagement of business, government, and community-based organizations. It is a remaking of the transportation and energy marketplaces with implications for global supply chains and efforts to mitigate and halt ecological damage. Given that the state is the fifth-largest economy globally, California's infrastructure and policy decisions have substantial implications for international trade and for the reduction of greenhouse gas emissions and global warming (Trencher et al., 2021). This transition is a case study of innovation in government policymaking and business–government relations. California's government leaders are working with businesses and civil society to change the supply of vehicles and create new market demands through the implementation of regulations, rules, standards, and the provision of grants and funds.

The importance of the transition to zero-emission vehicles cannot be understated. The transportation sector is the largest source of greenhouse gas (GHG) emissions in the U.S. In 2021, it contributed 28% of emissions, more than the electric power industry at 25% or the total manufacturing sector at 23% (U.S. EPA, 2023). In California, transportation accounts for 36.8% of the state's emissions, with heavy-duty vehicles contributing 8.8% (CARB, 2022). The Inland Empire (IE) in Southern California, where this study is placed, is known for its significant warehousing, logistics, and distribution industries, driven by its proximity to San Pedro Ports of Los Angeles and Long Beach and a vast network of freeways that facilitate the transportation of goods across the U.S. The IE is characterized by a mix of urban and suburban areas, and it also includes significant rural expanses and desert landscapes. There are approximately 8,000 transportation and warehousing facilities in the region to transport goods from the ports. This equates to hundreds of thousands of trucks registered in the region. While this situation places the IE prominently in the goods movement sector, it concurrently raises environmental concerns, particularly due to the significant number of MDHDVs traveling in the region (Hesse, 2020). As of April 2022, the American Lung Association ranked San Bernardino and Riverside Counties as the worst in the nation for ozone pollution. These counties also ranked in the top ten for the worst annual particle pollution nationally. The heavy concentration of diesel trucks and warehouse activities are a major contribution to these rankings. This all leads to the obvious—cleaner options are needed to improve the effectiveness and environmental impact of the transportation sector.

The MDHD fleet is a very complex set of vehicles to move from conventional fossil fuels to zero emissions, mainly because of their size and weight, and thus the energy needed to move them. In the transportation and logistics industry, vehicles are categorized based on their size, capacity, and purpose, with medium-duty (MD) and heavy-duty (HD) representing the two classes (Smith et al., 2020). MDVs manage moderate weights while retaining maneuverability. They are generally classified as Class 4–6 trucks and make urban delivery services using box trucks and specialized vans, and utility tasks using vehicles such as compact school buses. HDVs are classified into Classes 7–8 and are differentiated primarily by weight. Class 7 vehicles, including larger flatbed trucks, city buses, and smaller garbage trucks, have a Gross Vehicle Weight Rating (GVWR) between 19,501 and 26,000 pounds. Class 8 vehicles exceed a GVWR of 33,000 pounds. This class includes tractor-trailers, 18-wheelers, and heavy dump trucks (California Air Resources Board, 2021). The physical force required to move this amount of mass is considerable. Fossil fuels are currently the cheapest and most effective energy source, and changing this paradigm to zero-emission fuels means finding a source that can compete. The two main possibilities under discussion are hydrogen fuel cells and electricity. This research is focused on understanding the possibilities of electrifying the fleet, looking specifically at the opportunities for charging.

Key challenges to the use of electricity in the MDHD fleets include travel distance or range of the charge, and limited charging infrastructure. Many possibilities are emerging with advanced battery technologies, particularly in the realm of lithium-ion and solid-state cells. These new technologies enable larger vehicles to store and utilize energy more efficiently, making them increasingly viable for extended operations (Rangarajan et al., 2022; Matusiewicz, 2020). Additionally, telematics and smart management systems play a helpful role in optimizing routes and battery usage, enhancing fleet operational efficiency (Boriboonsomsin et al., 2024). The implementation of regenerative braking systems, which recover energy during braking, improves efficiency. Also essential is the development of fast-charging infrastructure, capable of servicing large batteries quickly to ensure operational efficiency (Jafari Kaleybar et al., 2023). The other large challenge is the amount of new information and working through the complexities of the transition to a zero-emission MDHD fleet.

Electrifying these vehicles has the potential to significantly reduce emissions, which could contribute to broader efforts aimed at environmental sustainability. However, it is crucial to examine both the advantages and the limitations of vehicle electrification thoroughly. This balanced evaluation will help in understanding the true impact of such a transition on emission levels and climate objectives. The careful phrasing and structured approach of this introduction aims to clarify what is currently known and identify the gaps in knowledge that this research seeks to address, ensuring that conclusions are drawn from well-rounded and precise analysis. Economically, the streamlined nature of electric drivetrains, characterized by fewer moving parts, suggests potential reductions in maintenance costs and increased operational longevity (Lukic et al., 2019). There are also plans to integrate MDHD EVs with investments in renewable energy, particularly wind and solar power. Improvements in the electric grid, supported by solar and wind infrastructure, bolster its capacity to meet the increased demand from electric vehicle charging, particularly during peak hours. Additionally, advancements in energy storage, like battery systems, enable storing surplus energy for consistent, reliable vehicle charging.

The transition to renewable energy powered vehicles brings many concerns about who will be the early adopters and market-driven stakeholders. The transition to electrification may adversely affect disadvantaged communities as small, independent companies and operators could struggle with the costs and complexities of adopting new technologies. These groups often lack access to the necessary financial support and resources available to larger entities, potentially widening economic disparities. Further analysis is required to understand and address these challenges effectively. Furthermore, workforce concerns exist, as many are not trained to work in electrification. Therefore, with this transition, social equity considerations are key so that everyone has a chance to benefit.

The government plays a crucial role in the transition to ZEVs in the MDHD sectors by establishing a policy framework that stimulates the market, including setting goals for manufacturers' sales and investing in new companies to supply the MDHD market with EVs. Public resources support this initiative through funding and incentives, bolstering demand for new technologies. However, significant costs pose a challenge. New all-electric heavy-duty trucks are priced at about half a million dollars, compared to $125,000 for a used diesel class 8 truck, and the necessary charging infrastructure, including temporary generators costing up to $250,000, adds financial burdens. Within this dynamic, considerations of social equity arise, focusing on the ability of many owner-operators and mid-sized firms to compete with larger multinational logistics and transportation firms. The market may eventually level, as large companies purchase new MDHD EVs and move them to the resale market, offering smaller firms a chance to buy these vehicles at a lower cost. This scenario places most of the transition risk on larger firms, who will be testing the new technologies. However, a majority of smaller firms, starting from an unequal position without adequate resources, might find the investment too high and the transition too complex, possibly forcing them to find alternative employment or retire from the sector.

The testing of the MDHD ZEV market began in the public sector, or more specifically, with transit fleets. California's Truck and Bus Rule from 2008 began the transition with public entities receiving public funding and support to test different zero-emission fuels and charging infrastructure. In the IE and the eastern Los Angeles region, Foothill Transit has been a leader in incorporating zero-emission buses into its fleet. Starting with electric buses and currently purchasing hydrogen vehicles, Foothill Transit is analyzing different conditions and configurations of the system for the diverse technologies. As part of ongoing research funded by CARB, Foothill Transit has developed fully electrified routes. Within these routes, electric buses can be fully charged in less than 10 minutes using two 500kW fast chargers within the bus route. (Foothill Transit Electric Bus Testing, 2023). However, there are still concerns regarding the effectiveness and reliability of this fleet. For example, if there is a power outage, the buses will not be able to charge. Therefore, Foothill Transit has recently adopted hydrogen fuel cell buses, but there are a number of concerns particularly with costs. The full case study on the transition to a ZEV fleet at Foothill Transit cannot be explored here, but it deserves mentioning as it is an interesting example of the tradeoffs that exist between alternate fuel and traditional vehicles.

This study seeks to delve deeply into the current and prospective dynamics of MDHDV operations in the IE. We begin with a review of the federal, state, and regional policies and programs that have been developed to support the transition to zero-emission vehicles. The next part looks at the current traffic patterns and volume of MDHDVs, with an emphasis on understanding origin-destination (OD), dwell times, and regional/short-haul (RSH) and long-haul (LH) trips in the region. This study also examines land use and the urban environment including variables of available land, truck parking areas, the electric grid, size of the fleet, and business characteristics. A critical aspect of the big data analytics will be to quantify the total fleet size, distinguishing between large fleet operators, independent owner-operators, and branch operations, and pinpointing their respective business locations within the region. Understanding these distinctions is essential for tailoring policies and infrastructure developments that address the specific needs and capabilities of each group, thereby ensuring a more effective and equitable transition to zero-emission vehicles.

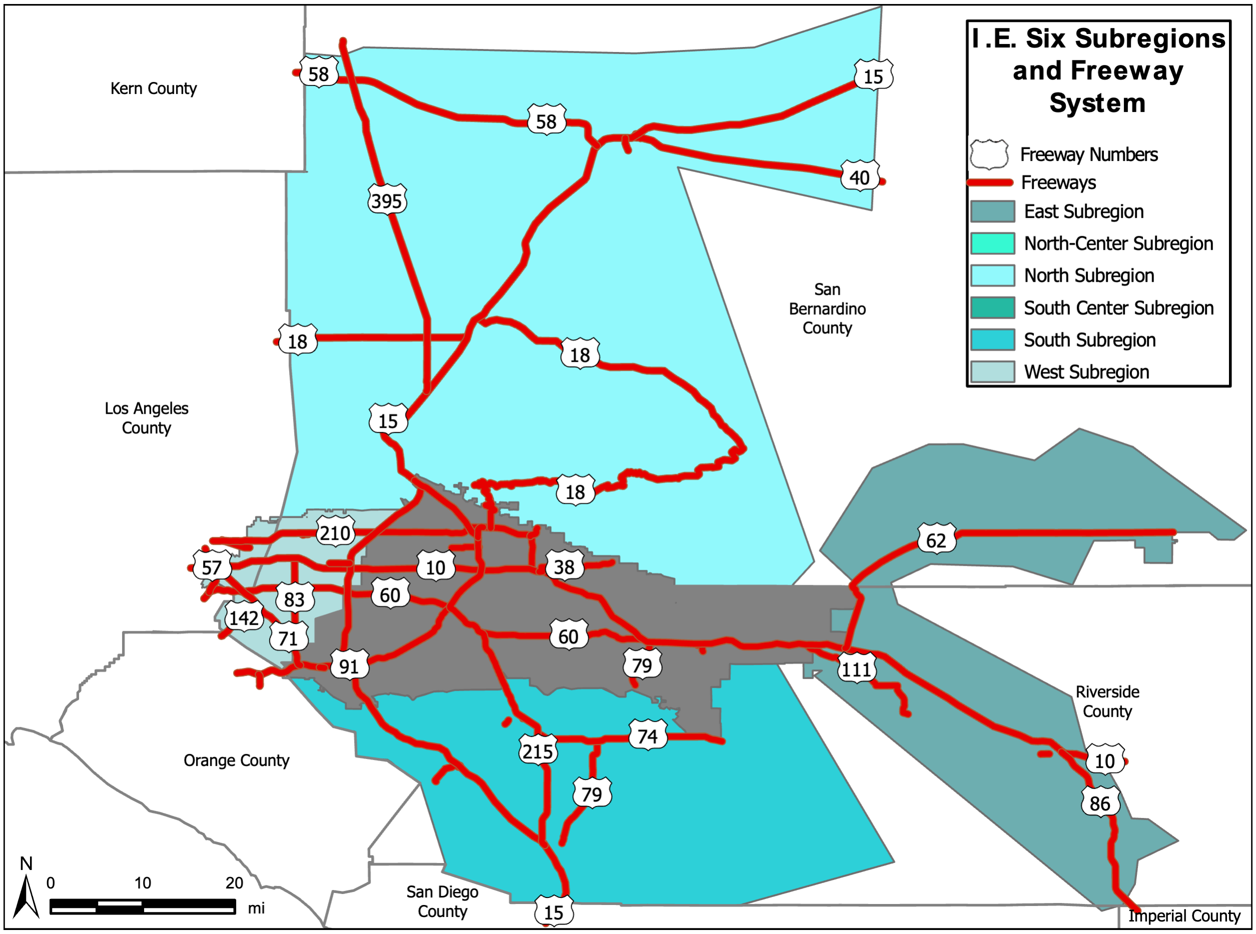
This report begins with an overview of the IE region and its importance as an inland port region. Next, we look at the specific methodology used to analyze the multiple sets of data collected. From here, we proceed with a descriptive review of key federal, state, and regional policies that have incrementally been developed for the past 50 years. The next section delves into the big data analysis, looking at the indicators described above. Then, the social equity implications and business considerations are explored. Finally, the research team developed a set of possible scenarios for developing an EV charging network for MDHD vehicles. This could provide alternatives to building out the charging infrastructure for MDHD EVs in the IE and could also be applied to other inland port regions such as Phoenix, Houston, Atlanta, and Columbus (CBRE, 2016). This potential network is discussed. Finally, as part of this research, we also conducted 16 interviews with regional experts from the public and private sectors to provide ground truth about the current system.

1.2 Area of Study: California's Inland Empire

The area of focus for this study is Inland Southern California, also known as the Inland Empire. For the purposes of this work, we define the IE as the two-county region of San Bernardino and Riverside, along with the cities of Pomona and Claremont in eastern Los Angeles County. This region is larger than many states, encompassing 27,444.46 square miles and is home to a population of 4.837 million. For comparison, the state of West Virginia is 24,230.04 square miles with a population of 1.783 million people, and South Carolina covers an area of 32,020 square miles with 5.191 million residents. To efficiently work with such a large land area, we divided the region into six subregions seen in Figure 1: East–Coachella Valley; North–Barstow and surrounding communities; North-Center–San Bernardino City and surrounding areas; South-Center–Riverside City and surrounding communities; South–Murrietta and Temecula region; and West–Ontario, Rancho Cucamonga, and surrounding areas.

The San Pedro Bay seaports of Los Angeles and Long Beach are approximately 65 miles from the West subregion of the IE. This port complex is the busiest container port in the United States. Annually, the Port of Long Beach handles about nine million twenty-foot equivalent units (TEUs), and the Port of Los Angeles handles around 9.9 million TEUs (Port of Long Beach, 2023; Port of Los Angeles, 2023). The enormous volume of goods flowing through Southern California's ports underscores the region's critical role in national and global commerce (Cetiner et al., 2019), but it also exacerbates environmental contamination. The intense activity at these ports, largely fueled by diesel-powered ships, trucks, and cargo equipment, leads to significant emissions of particulate matter and nitrogen oxides, contributing to air pollution and health risks for nearby communities. This duality highlights the urgent need to balance economic benefits with environmental impacts, making it a key area of concern for both policymakers and local residents. Goods arriving at these ports make their way to warehouses and distribution centers in the IE before being transported across the country. In 2017, the Port of Long Beach reported that almost 70% of the cargo moving out of the San Pedro ports is done by truck and 40% of the truck traffic is headed to the IE (Buck, 2017). Furthermore, from our analysis using Streetlight data, we found that 50% of bidirectional truck trips between the San Pedro ports and the IE originated from or were destined to the Port of Los Angeles, and 40% to the Port of Long Beach. Additionally, the San Ysidro land border with Mexico is approximately 75 miles from the South subregion, and the eastern California land port is approximately 100 miles from the East subregion. The IE is also bordered by Arizona to the east and Nevada to the north-east. The region's logistics capabilities are bolstered by an extensive network of major freeways, including the Interstate-10 (I-10), Interstate-15 (I-15), and Interstate-215 (I-215), also State Route 60 (SR-60), Interstate 40 (SR-40), and State Route 210 (SR-210), shown in Figure 1. This network facilitates the efficient movement of goods across the region and beyond. Finally, the region boasts several intermodal centers, and the presence of both BNSF Railway and the Union Pacific Railway's rail lines enhances its capacity for freight movement (Roy & Mitra, 2021).

Figure 1. Inland Empire: Six Subregions and the Main Freeways



This map illustrates the six subregions of the IE, each highlighted in distinct colors. The East subregion, in dark grey, predominantly lies in Riverside County, featuring the I-10 and I-86 freeways. The North subregion, in light blue, located in San Bernardino County, includes the north-south I-15 freeway and eastward I-40. The North-Center subregion, in dark blue, central in San Bernardino County, shows the intersection of I-10 and I-215. The South subregion, in light grey, adjacent to San Diego County, features north-south routes I-15 and I-215. The South-Center subregion, in dark grey and west of the East subregion, includes intersections of I-215 with SR-60 and SR-74. The West subregion, in light blue overlapping with Los Angeles County, incorporates the diagonally running I-10 and I-15, and the SR-60 freeway. These freeways link the subregions and connect them to the broader Southern California area.

According to the California Air Resources Board, the I-10, I-15, and I-40 are identified as top priority corridors in California (CARB Technical Memorandum, 2023). This prioritization is based on a comparative analysis of truck traffic metrics, including vehicle miles traveled, corridor length, average daily truck trips, and maximum truck volumes. These corridors ranked first, third, and fifth respectively in the state.

Leitner and Harrison (2001) did an extensive analysis of different types of inland ports that have been used to classify this region. The first is the larger designation of a Trade and Transportation Center Inland Port (Leitner & Harrison, 2001), "a location where border processing of trade is shifted inland and multiple modes of transportation are available in combination of value-added services" (p. 50). Within this definition, the IE is a large inland port region. It meets this general designation based upon the amount of trade and commerce moving through the region and has multiple specific inland port facilities. In 2016, CBRE Research identified the IE one of 12 major inland ports in the nation.

There are also a number of specific multimodal centers around the region, including the Ontario Airport, which is defined as an Air Cargo Port. Air cargo ports "exist in conjunction with passenger facilities but are becoming more common as dedicated cargo ports" (Leitner & Harrison, p. 50). The Ontario International Airport Authority, primarily known as a passenger airport, has expanded its operations to include cargo handling. In 2021, during the COVID-19 pandemic, it was recognized as the "fastest growing airport," according to Richards (2022). This growth might be attributed to an increase in cargo traffic as a response to shifts in global supply chains during the pandemic, though it is not specified if the designation was directly pandemic-related.

Additionally, there are three former air force bases that were closed throughout the region in the mid-1990s with the Base Realignment and Closure (BRAC) legislation. In 1997, the March Airforce Base in Riverside County was developed into an air cargo inland port facility named the March Inland Port. It is located in the South-Center subregion and is a joint-use facility with the United States Air Force providing access to air cargo, warehousing space, and workforce development training space (March Joint Powers Authority, 2022). The Southern California Logistics Airport Authority is located on the former George Air Force Base in Victorville, which is part of the North subregion for this study. George Air Force Base was another military base closed in the 1990s with BRAC and it currently provides facilities for aircraft manufacturing support services, general manufacturing, air flight operations and testing facilities, as well as workforce training facilities provided by Victor Valley Community College (Victorville, n.d.). The San Bernardino International Airport, located in the North-Center subregion, was the former Norton Air Force Base which was closed in 1994. The property was transferred for redevelopment to the Inland Valley Development Agency (IVDA) and the San Bernardino International Airport Authority (SBIAA). IVDA is working to create an industrial and commercial space for a number of different companies with connections to the Los Angeles region, Mexico, and various locations in the southeastern United States (IVDA, 2023). The SBIAA is working to expand commercial passenger traffic, has service with one low-cost airline, and plans for additional carriers. IVDA's focus on developing industrial and commercial spaces and SBIAA's expansion of commercial passenger traffic can both influence the regional transportation network and electrification infrastructure, supporting broader regional electrification goals. These facilities collectively enhance the regional capabilities in logistics, potentially easing the integration of electrified fleet operations and contributing to the overall sustainability goals of the study area.

The region also hosts Inland Container Ports. This is a specific "intermodal terminal facility that handles containerized shipments at a site away from a seaport" (Ramezani & Carr, 2022). Barstow, in the North subregion in this study, is set to host BNSF's Barstow International Gateway (BIG). This facility will cover 4,500 acres and will cost $1.5 billion (BNSF, 2023). The goal is to move cargo out of the San Pedro port complex as quickly as possible to alleviate truck congestion and improve supply chain flows. Additionally, a BNSF intermodal facility can be found in the City of San Bernardino, transferring containers from rail to truck and vice versa. This railyard has existed since the late 1800s and is being expanded to increase the efficiency of the facility and reduce train idling in the yard, which should positively impact noise and air pollution in the region (Progressive Railroading, 2022).

The IE also hosts a number of foreign trade zones (FTZs), allowing for the transfer of goods without tariffs or quota requirements. Within our study area, the FTZs include San Bernardino International Airport Authority; March Air Force Base; Victorville's Southern California Logistics Airport Authority; the City of Palm Springs; and the City of Palmdale. This region, with its vast network of transportation and warehousing facilities that support the twin ports of Los Angeles and Long Beach, is an ideal region to analyze the challenges of transitioning the MDHD fleet to EVs.

A key example can be found in the San Bernardino City/Muscoy unincorporated community in San Bernardino County. This area, located near the San Bernardino railyard and concrete batch, asphalt batch, and rock/aggregate plants, is impacted by on-site emissions generated by warehousing activities and the Omnitrans bus yard. Due to the high levels of air pollution and identified health impacts, the area has been recognized by South Coast Air Quality Management District as an AB 617 community. AB 617 was signed into law in 2017 to address the impact of air pollution on people in areas highly disadvantaged and designated as environmental justice communities. Implementation of AB 617 in a community consists of listening to the needs of the local stakeholders and developing a Community Emissions Reduction Plan (CERP). The CERP identifies area priorities to reduce air pollution emissions. From this plan a number of specific actions are designed, including additional regulation, incentives for the adoption of cleaner technologies, and outreach to help community members make informed decisions moving forward on the transition. Finally, air quality monitoring is used to help inform the community of pollution sources and improvements (SCAQMD, 2023). Within the IE there are a number of areas that live with high concentrations of pollution and are designated disadvantaged communities as seen in Cal Enviro Screen. Therefore, it is noted that much work needs to be done to mitigate and cease the mechanisms of environmental harm. It must also be taken into consideration that many families that are directly impacted by the emissions from these industries are also employed locally. The IE continues to thrive as a crucial hub in the global logistics and transportation network. It is crucial to adopt and enforce sustainable practices that balance economic growth with environmental responsibility. This transformation must consider not only air quality improvements and reductions in greenhouse gas emissions but also broader environmental pollutants that affect the region. Such an approach should include economic strategies to ensure that the shift does not disproportionately impact families, especially those in economically disadvantaged communities. It is essential to identify the major contributors to emissions within the region—typically large logistics and manufacturing firms—and hold them accountable for their environmental impact. This accountability extends beyond simply addressing greenhouse gases to encompass a wide range of pollutants that contribute to local air quality issues. By fostering a gradual and inclusive approach to adopting green technologies and practices, the IE can ensure that all communities benefit equitably from this new phase of economic and environmental development.

2. Methods

2.1 Introduction

This study is working from the policy and market changes that are driving the zero-emission transition of MDHD vehicles. More specifically, it looks to understand the possibilities for MDHD EV charging infrastructure in the IE to support this transition. This study is focused on government actions, business and market possibilities, and social equity considerations. It is a review of the government–business system and the impacts on the community as seen by several industry stakeholders. This work was done in conjunction with an analysis of the IE's transportation and urban systems using big data analytics. Using a mixed-methods approach, we have a holistic view of the transition to MDHD EVs in the IE through the actions of government, business, and community leaders, and a scholarly understanding of how the transport system functions. Our methodology is unique, as it allows for an integrative examination of multiple perspectives and data sources, providing a comprehensive understanding of the complex dynamics at play in the electrification of the transportation sector.

Several datasets were used throughout this report. Specifically, we conducted a systemic literature review analysis to examine policies that speak to the ZEV transition, new energy regimes, and social equity; a geospatial analysis; a big data analytics assessment to define and discuss transport and urban systems; and an interview-targeted thematic analysis to look into the perspectives of local leaders in government and business on how it is expected to work. The remaining parts of this report explore the following research questions:

Part II: Government Engagement

- What are the current federal and state policies related to ZEV MDHD?
- What are the potential policy-related needs that will assist with the transition to a ZEV system?

Part III: Transportation and Urban Systems Analysis

- What are the current traffic patterns and volume of MDHD vehicles in the IE? What are the OD trends of these trips, looking at both drayage and long-haul trips?
- Where are the locations for MD/HD vehicles to park, rest, and refuel in the IE?
- What are the logistics and distribution centers' characteristics (type, size, location) in the IE?

- What is the total fleet size by owner (large fleet operators, independent owner-operators, and public fleets) and where are the businesses located in the region?

- Where are possible locations for the buildout of the EV charging infrastructure for MDHD EVs?

- What are the feasible alternative solutions/options to support charging MDHD EV in the IE?

Part IV: Social Equity and Business Considerations

- How could the build-out of the EV infrastructure and switch to MDHD EV impact low-income and/or disadvantaged residents in the IE?

- How does this overlay with the region's demographic/environmental justice and charging infrastructure maps?

- What are the equity considerations for the implementation of EV technology?

2.2 Systematic Literature Review Analysis

- The systematic literature review encompassed a comprehensive evaluation of policies at various levels and sectors of governments in the U.S., California, and regionally. At the federal level, a review of federal legislation, Presidential Executive Orders, and the rules and standards set by various federal agencies was conducted. For California, we looked at state legislation, Executive Orders passed by two Governors, and the rules, resolutions, and agreements passed by state agencies, particularly the California Air Resources Board.

At the regional and local levels, the review considered the contributions of several governing bodies, including policies on MDHD EVs from key organizations. Notably, the Metropolitan Planning Organization, the Southern California Association of Governments (SCAG), as well as regional Councils of Governments, the San Bernardino Council of Governments and the Western Riverside Council of Governments have all played significant roles in shaping these policies. Additionally, programs like JETSI (California's Joint Electric Truck Scaling Initiative) and eTRUC-RHETTA (California's Research Hub for Electric Technologies in Truck Applications) were included to understand their specific contributions toward regional transition. The involvement of utility companies in supporting the EV infrastructure and transition was also a critical part of the review, as their role is pivotal in the broader context of ZEV adoption.

This comprehensive review methodically evaluated the effectiveness, impact, and implications of various legislative and regulatory efforts across these different levels of government. It was not limited to assessing their evolution, but also involved understanding their interaction within a larger, multi-tiered governance framework. The objective was to provide an overview of the policy landscape shaping the ZEV transition, identifying gaps, and offering insights for future policy development.

The methodology adopted for this systematic literature review on the business aspects of MDHD EVs was structured to provide a deep dive into the economic, operational, and strategic elements of this sector, with a particular focus on charging infrastructure and the implementation of opportunity charging systems. The literature search strategy was expansive, encompassing academic research, industry reports, and case studies from a variety of sources including business journals, automotive and energy sector publications, and economic analyses.

2.3 Geospatial Analysis

For the purposes of this study, the IE is defined by the full 27,000 square miles in Riverside and San Bernardino counties, along with the cities of Claremont and Pomona in the eastern portion of Los Angeles County. This region is diverse in geography and natural environment, as well as the geospatial relationships with adjoining regions. As seen in Figure 1, we divided the IE into six subregions based on their unique social, economic, and geographical attributes—East, North, North-Center, South, South-Center, and West. This division is a crucial element of our geospatial analysis. By delineating these subregions, we facilitated a more nuanced examination of the region as a whole, enabling us to analyze the interactions among these subregions and their individual contributions to broader regional dynamics. This approach provides a clearer understanding of how regional policies and initiatives might be tailored to address the distinct needs and challenges of each subregion, thereby enhancing the effectiveness of interventions aimed at promoting sustainable development and economic growth.

To further optimize the spatial analysis within the study, a hexagonal tessellation with an area of 6.5 square miles per hexagon due to our limitation of number of zones used in StreetLight Data was executed in ArcGIS Pro. To determine the side length of a hexagon for the desired area, the following formula was employed:

$$Area = \frac{3\sqrt{3}}{2} \quad s^2$$

The term s^2 describes the square of this side length. The coefficient is a geometric constant derived from aggregating the areas of the six equilateral triangles that constitute the hexagon when it is segmented accordingly. Subsequently, the "Generate Tessellation" tool was utilized, selecting "Hexagon" as the tessellation type, and inputting the calculated side length. The grid's extent was set to the study area boundary. Post-creation, the "Calculate Geometry" tool in ArcGIS pro verified that hexagons closely matched the target area of 6.5 square miles (Figure 3). By using a hexagonal tessellation, the study benefits from a more uniform and efficient division of the space compared to traditional square or rectangular grids. Hexagons minimize edge effects and reduce the variability in adjacency relationships between units, leading to more accurate spatial analyses.

Figure 2. Hexagonal Grid Tessellation Analysis of the Inland Empire

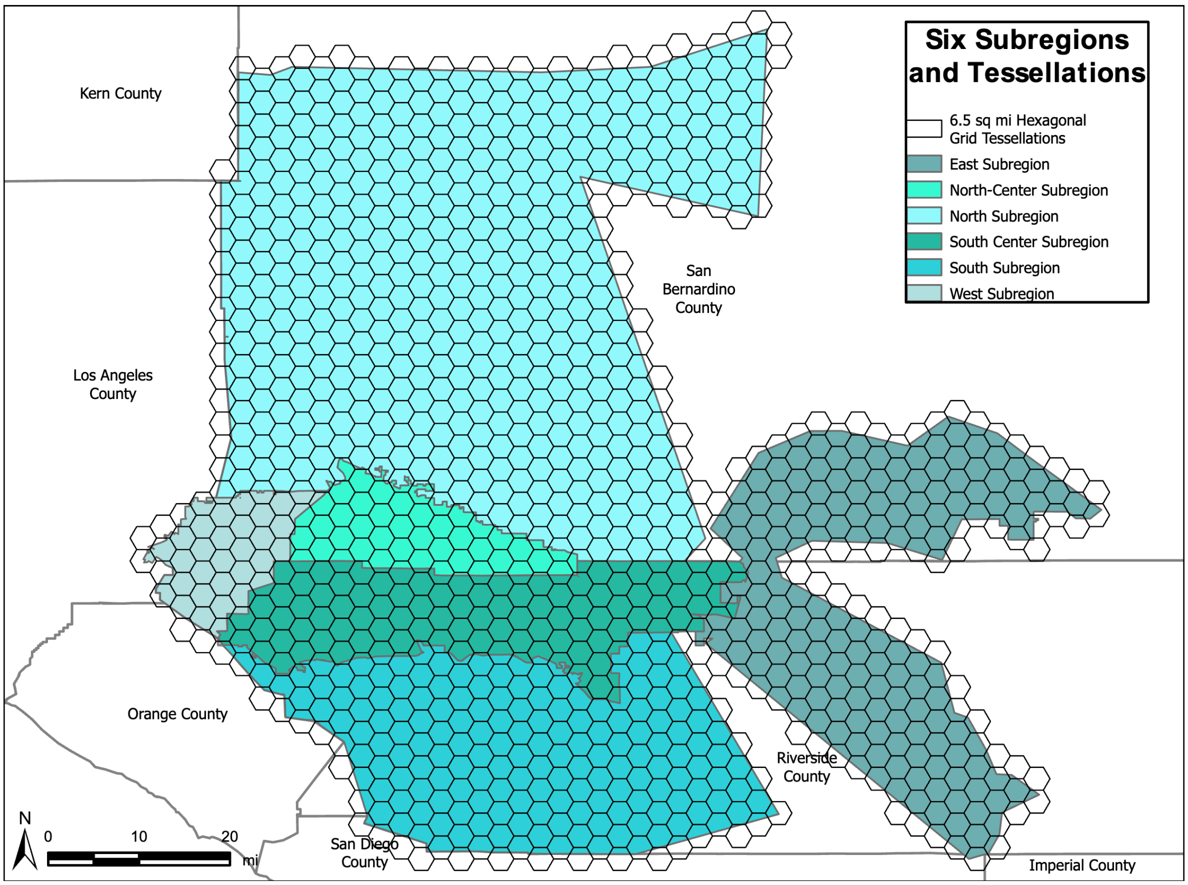


Figure 2 shows the lay of the land when the tessellation grid was integrated with other GIS datasets, with spatial joins and overlays adapted to the broader study's objectives. For visualization, a thematic map was crafted using the "Symbology" panel in ArcGIS Pro, employing varying color gradients or symbols to signify different data attributes within the hexagons. It is important to note that the precision of the tessellation depends on factors such as the study area boundary definition, spatial reference system, and subsequent geospatial analyses. The properties of hexagons, primarily their equidistant spacing to adjacent cells, provided a uniform basis for spatial analysis and ensured consistency in the calculation of distance-related metrics (Yang et al., 2021). This was particularly beneficial when examining travel patterns and dwell times for MDHDVs, as it allowed for a more precise representation of MDHDVs' operational spaces. Furthermore, the hexagons' coverage and minimized perimeter length facilitated accurate and visually coherent mapping of data. This enhanced the analysis of regional traffic flows and infrastructure. The reduced edge effects and the closer approximation to circularity inherent in hexagonal grids meant that the modeling of MDHDVs' movements and stoppages was less distorted compared to other shapes, which could have significant implications for understanding the region's dynamics. In essence, hexagonal tessellations provided a geometrically efficient, uniformly distributed, and visually intuitive framework which elevated the analytical rigor and clarity of the study's findings as well as making it easier to compare smaller regions.

2.4 Big Data Analytics

Big data analytics allows for a specific deep dive into each subregion and tessellation for a greater understanding of the movement of vehicles and the relationships to urbanized areas, business locations, fleets, and dwell times. The full array of datasets used to develop the analysis for this study are found in Table 1. StreetLight Data (StL Data) provides access to the OD analysis and truck dwelling analysis (Streetlight Data, 2021). The ESRI Business Analyst – Data Axle link provides detailed information about the types of business data available, which includes industry-specific details that are crucial for understanding the economic cycle of the IE (Data Axle, 2021). The California Air Resources Board Fleet Database link allows access to registered truck data to understand the composition of the truck fleet in California (California Air Resources Board, 2021). The California Energy Commission provides comprehensive data on the public electric utilities in the region. The Caltrans Parking Study offers insights into the availability and distribution of truck parking. This helps to determine where drivers are likely to rest and how this might influence the placement of charging stations. Lastly, the Southern California Association of Governments (SCAG) GIS Open Data site provides detailed land use data and where there might be opportunities or constraints for infrastructure development.

Table 1. Key Data Sources

Feature	Data Type	Source	Year
Traffic Patterns	Vehicle counts, travel miles	Streetlight Data	2021
MDHDVs Dwell Times	Duration and county of vehicle stops	Streetlight Data	2021
Business Locations	Business count, types, sizes	ESRI Business Analyst – Data Axle (codes were selected based on a SCAG Freight Study in 2018)	2021
Truck Registrations	Number of registered trucks, emission data	California Air Resources Board Fleet Database	2021
Utilities	Energy production	California Energy Commission	2021
Parking Availability	Number and location of truck parking spaces	Caltrans Parking Study (a one-time study)	2022
Land Use	Land use parcels	Southern California Association of Governments	2019

StL Data provides a dataset derived from multiple technologies, including cellular networks, GPS, and telematic devices. The data is collected through applications on cell phones, telematic devices, and other tools, and provides the aggregation of vehicular movement. An additional service provided by StL Data for this study was MDHD truck dwell times (resting) by location and duration. This helped to differentiate between long-haul (LH) and regional short-haul (RSH) trips and provided insight into vehicle movements over various distances.

Regional short-haulers include medium- and heavy-trucks (Class 5–8) per the Federal Highway Administration's classification, catering to shorter trips, generally within 150 miles, within a single state or between neighboring states (Hunter et al., 2021). A significant part of regional short-haul trucking includes drayage, defined by the transport of goods between seaports, railyards, and warehouses. This is a key element in the intermodal transport chain, connecting longer transportation legs with regional distribution (Gronalt et al., 2019). Additionally, regional short-haul trucking plays a crucial role in moving goods between distribution centers and warehouses, and also in last-mile delivery. Last-mile delivery is the final step in the delivery process, where goods are transported from a distribution center or warehouse to the destination, typically a retail store or consumer's home (Halldórsson & Wehner, 2020). This segment of trucking is critical for the timely and efficient delivery of goods, especially in the era of e-commerce where consumers expect quick and reliable delivery services (Farooq et al., 2019). Drivers in this sector frequently load and unload goods, which could provide a chance for opportunity charging. Additionally, the drivers generally return home daily after driving 150–250 miles per day.

Long-haul (LH) drivers are defined as those who transport freight over extended distances, typically exceeding 250 miles. Long-haul trips often involve transporting goods over extensive distances, often across multiple states or from coast to coast (Romero-Silva & Mujica Mota, 2022). These operations typically require Class 7 or Class 8 trucks. The main difference is the cab used by the drivers, with LH trips typically made with larger sleeper cabs. Drivers of these vehicles often spend several days to weeks on the road, facing challenges such as managing fatigue, maintaining concentration for long hours, and adapting to diverse weather and road conditions (Shandhana Rashmi & Marisamynathan, 2023).

An important part of this study was capturing trips within the IE and trips coming into the region from locations outside. A limitation was decreased data coverage with the increase of the geographic area. This is a common issue in spatial analysis. As the area of analysis increases, the density of data capture often decreases due to limitations in the data collection methods. In addition, StL has a limitation of a 90,000 square mile area; any area larger than this value cannot be analyzed. To overcome this barrier and to be able to compare the RSH data with the LH data, the output file offers two matrices:

- OD traffic: An StL index created using machine learning algorithms reflecting the volume of trips from the origin zone to the destination zone.
- Destination Zone Traffic: An StL index created using machine learning algorithms showing the total trip volume to the destination zone with no limitation on where they came from.

These two matrices are subtracted to reflect the LH trips.

Figure 3. Regional Short-Haul Operational Buffer Analysis for the Inland Empire with Centroid and Hexagonal Grid Overlay

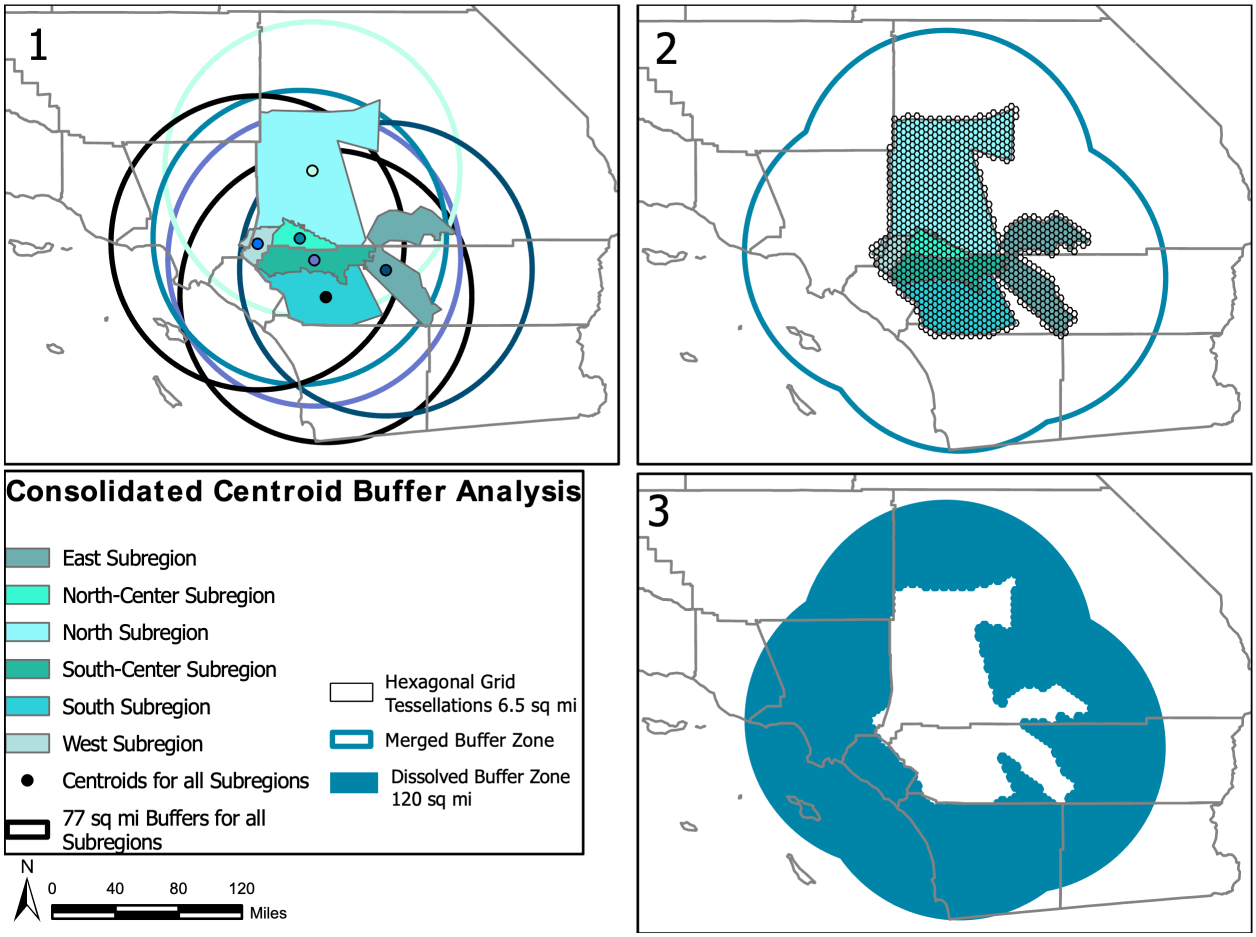


Figure 3 offers a visual analysis of the IE, segmented into different subregions, with a focus on RSH transportation. Map 1 depicts various subregions within the IE, each identified with a unique color. The centroids, marked by dots, represent the central points of these subregions. Around each centroid, circular buffers with a radius of 77 miles are drawn, which represent the average operational range for RSH trips within the respective subregions. This cut-off point was extracted from the technical memorandum from the state of California in 2023 (State of California, California Transportation Commission, 2023). Map 2 overlays a hexagonal grid, with each cell covering an area of 6.5 square miles, upon the same region. This grid is used to analyze data within precise geographic units. Map 3 consolidates the individual buffers from Map 1 into a single, merged buffer zone, which encompasses the collective operational area for RSH trips across the subregions. The outer boundary of this merged area defines the extent of the RSH buffer zone. The blue shade represents the dissolved buffer zone that may have been calculated by merging the individual subregion buffers and then dissolving the boundaries to create a single contiguous area. This contiguous buffer delineates a unified operational zone for RSH trips that cross subregional boundaries within the IE.

Streetlight Data is integrated with OpenStreetMap for geospatial mapping capabilities. This step aids in the geographical visualization and interpretation of the data. Additionally, the StL Data platform allows for the demarcation of geographical areas of interest, termed "zone sets," which can range from intersections to regional territories. This feature enabled the research team to import geographies to examine traffic patterns within the identified zones or tessellations used for this study.

One limitation to this service is a lack of real-time data delivery, but the historical data was applicable for this study. Another issue is that data provided are not actual counts, but an index based upon an algorithm that contextualizes, aggregates, and normalizes the data. To make sure the data provided was accurate, the research team validated the StL Data through a comparative analysis of traffic data provided by SCAG and Caltrans.

The comprehensive analysis presented in Figure 3, alongside Streetlight Data and OpenStreetMap integration, enhances our understanding of geographic and operational dynamics within the IE, particularly for RSH transportation. By segmenting the IE into subregions and applying a hexagonal grid, the study precisely localizes traffic patterns, facilitating strategic planning for route optimization and infrastructure development, such as strategically located charging stations. The unified buffer zone delineates an operational area accommodating the range of RSH trips, which is crucial for planning the electrification of the fleet. Despite the limitations of real-time data availability, the historical traffic data, validated against sources like SCAG and Caltrans, supports robust conclusions about potential charging opportunities.

2.6 Interview Targeted Thematic Analysis

Sixteen regional experts from government and business were interviewed for this study. The interview transcripts were closely analyzed using an interview-targeted thematic analysis to identify common themes and patterns. Given the specific focus on statements that stand out, this method is particularly effective in highlighting the most significant or prevalent opinions, concerns, and perspectives among the interviewees. The researchers had the ground-truthing experience to obtain the voices of the stakeholders and the community.

The government participants were drawn from various levels, including state, regional, and local agencies. Similarly, the business representatives comprised a diverse group, including those from utilities, manufacturers, and a mix of drivers and owner-operators of MDHDVs. The interviews served as a means of ground-truthing the other data. This component of the research included an analysis of existing policies and a review of business impacts, contributing to a more comprehensive understanding of the real-world implications of MDHD EV electrification. Through this process, we were able to correlate our theoretical findings with practical observations, enhancing the reliability and relevance of our research.

Part II: Government Engagement

3. Federal, State, and Regional Action

3.1 Introduction

The use of vehicles to transport people and goods in the United States is seen as a way of life. However, this independence in mobility options has greatly harmed the environment (air quality and greenhouse gas emissions responsible for climate change) and human health (CARB, 2022). Governments have been regulating and working to reduce atmospheric pollution since the 1950s and 1960s. This involvement came about because of need, particularly in Southern California, where levels of smog and pollution were so high that children had to stay home from school, and it was impossible to see the mountain ranges surrounding much of Southern California's urban areas (Morrison, 2023). The rules implemented and changes made to fuel type (e.g., elimination of leaded gas, new cleaner diesel) cleaned a large portion, but more is needed.

The current transition to zero-emission vehicles is comparable to the advent of the combustion engine. It has been a long time coming and will not be fully implemented for a number of years, as it is not a simple task. This transition entails a full reorganization of the vehicle and energy markets, and how goods and people move through the system. Movement and transportation linkages are the backbone of any community. Transportation linkages keep the economy flowing, help social interactions span distances, and make networked learning and engagement with the world possible. Transportation infrastructure, how it functions, and what options people have in how they move themselves and things can lead to a strong or a struggling region. Infrastructure development has been a core debate in American politics since the founding of the nation. At the federal level there have been successes and failures in improving the transportation system. The same can be said for California, but an ultimate goal of improving the environment while also maintaining economic prowess has been a long-term goal.

Government, as the steward for the public realm, has taken a number of actions to improve the transportation system, the environment, and as a consequence public health. The public system in the United States is a mix of actors. The federal government's role includes providing grants and loans, and also setting standards across the nation. This, of course, has a number of positives and negatives, as stakeholders and power across the nation are as diverse as its people. Not all have the same environmental concerns, and there are many differing economic interests. This can make policymaking at the federal level a complex and lengthy process.

States can be much more specific as to what happens within their boundaries, and California in particular obtained a special waiver in the Federal Air Quality Act of 1967 to set its own air pollution standards. California established its ambient air quality standards (CAAQS) in 1962, before the establishment of the U.S. EPA and the national ambient air quality standards (NAAQS), which were set in 1971. Even though the state has its own, stricter air quality standards, there is no requirement for them to be met by specific dates. The requirements exist to show incremental progress at the local level to meet attainment of the state standards. There are regional air quality management districts that are mandated to meet federal air quality standards to be in compliance and avoid penalties (CARB, 2023a). They report to the state and federal governments through the State Implementation Plans (SIPs) established by the 1970 Clean Air Act.

In 1966, the first motor vehicle emissions standard in California and the nation was established. Within these standards was a requirement set by the California Bureau of Air Sanitation, which one year later, in 1967, merged with the California Motor Vehicle Pollution Control Board to create the California Air Resource Board (CARB). CARB is California's regulatory agency in charge of the rules and regulations for mobile and stationary emissions. Therefore, the phase-in of zero-emission vehicles is being primarily implemented by CARB.

The legislative and executive branches of the federal and state governments are engaged with policy making for the transition to zero-emission vehicles and renewable energy generation. This is seen in the legislation passed by Congress and the state legislature, and in the executive orders by both the President and the Governor, in addition to the subsequent rules established by executive branch agencies. It can take many years to get a major piece of legislation passed at the federal level with many competing interests, particularly in established industries. To add to the politics of decision-making, in recent years, particularly at the federal level, Congress has been divided along partisan lines, and presidential executive orders (EOs) have become a larger part of governance within the renewable sector. At the state level, more action has been taken by the legislative branch, many times with direct involvement of the Governor. In California, environmental policies have been incrementally evolving to meet global warming and GHG emissions demands. Though not all stakeholders in the state agree, there is general support for more restrictive policies on major polluters.

3.2 Federal Actions

In this section of the study, federal policies, executive orders, and agency rules are reviewed to show the progression towards alternative fuel vehicles. This policy framework is focused on environmental regulations, new engine technologies, alternative energy generation and storage, and the funding to support state/local governments and businesses with the transition. This work has not happened overnight and has taken an incremental approach over the past 50 years. Table 2 provides a listing of federal legislation that has led to the transition to ZEVs.

Federal Legislation

The beginning of federal government action on environmental protection goes back to the 1950s and 1960s. The federal government passed the Clean Air Act (CAA) in 1963, which was the first act to control air pollution. It began the monitoring of air quality, and in 1967 the Air Quality Act was passed, which expanded the role of the federal government. In 1970 the Clean Air Act was passed, which set the first standards for air pollution from mobile and stationary sources. From this came the National Ambient Air Quality Standards, State Implementation Plans, New Source Performance Standards, and National Emission Standards for Hazardous Air Pollutants. The Environmental Protection Agency (EPA) was developed at the same time as the National Environmental Policy Act in order to manage the CAA. From this point on, advancements in technology have improved upon the monitoring of air pollution, developed new sources of energy and fuels, and created the engines that could run on the new energy sources. In 1990, the CAA was amended and further increased the role of the federal government in monitoring and regulating air pollution. The Clean Air Act Amendment (CAAA) (PL 101-549) was particularly significant because of its role in establishing a framework for alternative fuels and tighter pollution standards for vehicles, increasing the regulatory authority of the EPA, and establishing initiatives to reduce emissions from mobile sources (U.S. EPA, 2022; U.S. Department of Energy, n.d.).

Table 2. Federal Legislation Supporting the ZEV Transition, 1970–2023

Year	Public Law (PL)	Short Title
1970	91-604	Clean Air Act (CAA)
1975	94-153	Energy Conservation Act (EPCA)
1988	100-494	Alternative Motor Fuels Act (AMFA)
1990	101-549	Clean Air Act Amendments (CAAA)
1991	102-240	Surface Transportation Efficiency Act (ISTEA)
1992	102-486	Energy Policy Act
1998	105-178	Transportation Equity Act for the 21st Century (TEA-21)
2005	109-59	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)
2005	109-58	Energy Policy Act
2007	110-140	Energy Independence and Security Act
2008	110-343	Energy Improvement and Extension Act
2009	111-5	American Recovery and Reinvestment Act
2010	111-312	Tax Relief, Unemployment Insurance Reauthorization, and Job Creation Act
2010	111-364	The Diesel Emissions Reduction Act (DERA)
2012	112-141	Moving Ahead for Progress in the 21st Century Act (MAP-21)
2012	112-240	American Taxpayer Relief Act
2014	113-295	Tax Increase Prevention Act
2015	114-94	Fixing America's Surface Transportation Act (FAST)
2016	114-113	Consolidated Appropriations Act
2020	116-94	Further Consolidated Appropriations Act
2021	116-260	Consolidated Appropriations Act
2021	117-58	The Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act)
2022	117-169	Inflation Reduction Act

The Clean Air Act (CAA) of 1970, the Energy Policy and Conservation Act (EPCA) of 1975, the Surface Transportation Efficiency Act (ISTEA) of 1991, and the Energy Policy Act (EPAct) of 1992 were instrumental in setting the standards for the current policy regime. The CAA broadened the regulatory powers of the EPA and set the federal standards for air quality and emissions. The EPCA set the Corporate Average Fuel Economy (CAFE) standards to improve motor vehicle efficiencies and provide the U.S. Department of Transportation National Highway Traffic Safety Administration (NHTSA) with the authority to monitor and regulate the standards. It also required the U.S. Department of Energy to provide the public with an annual fuel economy guide.

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 established the Congestion Mitigation and Air Quality Improvement Program (CMAQ). This program provides funding to reduce mobile emissions in non-attainment and maintenance areas established under State Implementation Plans. ISTEA was followed by TEA-21 (the Transportation Equity Act of the 21st Century) in 1998. TEA-21 was a major transportation funding bill with a specific focus on transit and transportation infrastructure. This legislation was followed by SAFETEA-LU in 2005, which focused on "improving safety, reducing traffic congestion, improving efficiency in freight movement, increasing intermodal connectivity, and protecting the environment" (FHWA, 2005, para. 2). The MAP-21 in 2012 provided funding and continued many of the programs first developed in 1991. Finally, the FAST Act in 2015 built upon MAP-21 and developed a new program to better manage the movement of freight across the nation. Specifically, the FAST Act mandated the Federal Highway Administration (FHWA) to establish a National Freight Network, which includes the Primary Highway Freight System (PHFS), critical rural and urban freight corridors, and locations in the interstate system not included in the PHFS.

The EPAct in 2005 built upon the Energy Conservation and Protection Act. The EPAct was passed to reduce U.S. reliance on petroleum and improve air quality through renewable fuels, energy projects, and improved energy efficiency. The Diesel Emissions Reduction Act (DERA) of 2010 amended the EPAct of 2005, and authorized additional funds for EPA to provide grants and loans to reduce the level of emissions from diesel engines. DERA was reauthorized in the Consolidated Appropriations Act in 2021.

The Bipartisan Infrastructure Law (BIL), also known as the Infrastructure Investment and Jobs Act of 2021, and the Inflation Reduction Act (IRA) of 2022 are pivotal in supporting the transition ZEVs in the U.S. The BIL focuses on developing the necessary infrastructure, such as EV charging stations, and providing incentives for both manufacturers and consumers. The IRA complements this by offering tax credits and financial incentives to make EVs more affordable and to stimulate domestic production of EV components. Together, these acts promote a comprehensive shift towards a sustainable transportation system, enhancing environmental and economic resilience by supporting the adoption of clean energy technologies. The goals listed for the BIL include "rebuild America's roads, bridges and rail, expand access to clean drinking water, ensure every American has access to high-speed internet, tackle the climate crisis, advance environmental justice, and invest in communities that have too often been left behind" (The White House, 2023). Looking specifically at the zero-emission transition, it appropriates $110 billion in funding to improve roads and bridges focusing on climate change mitigation, resilience, equity, and safety. It also provides $17 billion for port infrastructure and waterways and $25 billion for airports and to implement electrification and other zero-emission technologies. To support energy production, an important component of the zero-emission transition, $65 billion was allocated for clean energy transmission and grid upgrade (The White House, 2023).

The Inflation Reduction Act was designed to reduce energy costs by building a new energy system with the support of clean energy projects. A main goal is the reduction of carbon emissions by 40% by 2030.

> The theme across all this is the clean energy transition, it is private sector-led, but government-enabled. So, we as a government are trying to enable the private sector to move faster so we can meet our very ambitious goal, which includes a 50% reduction from 2005 levels of greenhouse gas pollution by 2030, a carbon pollution-free power sector by 2035, and a new zero emissions economy by 2050 (U.S. Department of Energy, 2023).

In order to accomplish this goal, the IRA allocates "$369 billion to modernize the U.S energy system in 2022" (U.S. Department of Energy, 2023, para. 7).

As seen here, the federal legislation builds upon previous actions taken by Congress with a goal of improving the system. These laws provide the federal structure and appropriations to change the transportation and energy systems with the focus on reducing greenhouse gas emissions. Initially driven by concerns over air pollution, the shift toward zero-emission vehicles has evolved, with global warming and GHG emissions now serving as the primary motivators. This evolution is significantly influenced by recent legislation, including the Bipartisan Infrastructure Law and the Inflation Reduction Act, which collectively provide a robust framework and substantial funding that directly supports the goals of this study to advance the adoption of cleaner transportation technologies within the study context.

Presidential Executive Orders

Executive Orders (EO) have been used by Presidents over the years to provide administrative tasks and oversight of executive agencies. EOs are designed to give direction to federal agencies regarding the implementation of new legislation, creation of task forces, administrative actions, and during times of conflict in the legislative branch to implement new policies. There have been 15 EOs since 1993 that support the transition to zero-emission technologies. Many of the EOs seen in Table 3 direct federal agencies to adopt cleaner fuel technologies, develop interagency task forces to support legislation passed by Congress, and mandate how federal dollars are spent through agency programs. Of particular note is EO 14096—Justice40—which mandates that 40% of all federal dollars must be spent in marginalized communities to help overcome environmental justice challenges in communities that "are marginalized, underserved, and overburdened by pollution" (The White House, 2023, para. 1).

Table 3. Presidential Executive Orders Supporting EV Transition and Environmental Justice, 1993–2023

Year	Executive Order (EO)	Short Title	Presidential Admin.
1993	12844	Federal Use of Alternative Fuel Vehicles	Clinton
1994	12898	Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations	Clinton
1998	13101	Greening of Government Through Waste Prevention, Recycling, and Federal Acquisition	Clinton
2000	13148	Greening the Government Through Leadership on Environmental Management	Clinton
2000	13149	Greening the Government Through Federal Fleet and Transportation Efficiency	Clinton
2001	13212	Actions to Expedite Energy-Related Projects	GW Bush
2007	13423	Strengthening Federal Environmental, Energy, and Transportation Management	GW Bush
2009	13514	Federal Leadership on Environmental, Energy, and Economic Performance	Obama
2013	13653	Preparing the United States for the Impacts of Climate Change	Obama
2015	13693	Federal Leadership on Climate Change and Environmental Sustainability	Obama
2021	13990	Climate Crisis; Efforts to Protect Human Health and Environment and Restore Science	Biden
2021	14008	Tackling the Climate Crisis at Home and Abroad	Biden
2021	14057	Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability	Biden
2022	14082	Implementation of the Energy and Infrastructure Provisions of the Inflation Reduction Act of 2022	Biden
2023	14096	Revitalizing Our Nation's Commitment to Environmental Justice for All	Biden

Rule Making

Under the Administration Procedures Act (APA), federal agencies can develop policies through the rule making process. The first rule or standard was set by the Environmental Protection Agency (EPA) in 1976 to set the emission standards for heavy-duty engines as seen in Table 4. All other emission standards build upon this decision. Twenty years later, the federal EPA began a rule making process to combat air pollution, smog, and soot. As seen in Table 4, there are several rules that were passed between the mid-1990s until the 2010s with a specific focus on reducing emissions from heavy-duty engines that contribute to air pollution. In 2011, EPA made the first of three joint rules with NHTSA to reduce emissions that are contributing to global warming and GHG emissions. These rules were developed in conjunction with California Air Resources Board input and led to the CARB regulation on Tractor-Trailer Greenhouse Gas (TTGHG) Regulation passed in 2008 (see Table 8).

Table 4. Federal Agency Rules and Standards that Support the EV Transition, 1976–2023

Year	Agency	Rule/Standard Title
1976	EPA	40 CFR part 86 – Emission Standards for Heavy-Duty Engines
1995	EPA	Final Rule for on Ozone Transport Commission; Low Emission Vehicle Program for the Northeast Ozone Transport Region
1997	EPA	Final Rule for Control of Emissions of Air Pollution From Highway Heavy-Duty Engines
2000	EPA	Final Rule for Control of Emissions of Air Pollution from 2004 and Later Model Year Heavy-Duty Highway Engines and Vehicles; Revision of Light-Duty On-Board Diagnostics Requirements
2001	EPA	Final Rule for Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements
2002	EPA	Final Rule for Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines: Non-Conformance Penalties for 2004 and later Model Year Emission Standards for Heavy-Duty Diesel Engines and Heavy-Duty Diesel Vehicles
2005	EPA	Final Rule for Control of Emissions of Air Pollution From New Motor Vehicles: In-Use Testing for Heavy-Duty Diesel Engines and Vehicles
2005	EPA	Final Rule for Modification of Federal Onboard Diagnostic Regulations for Light-Duty Vehicles, Light-Duty Trucks, Medium-Duty Passenger Vehicles, Complete Heavy-Duty Vehicles and Engines Intended for Use in Heavy-Duty Vehicles and Engines Intended for Use in Heavy-Duty Vehicles Weighing 14,000 Pounds GVWR
2006	EPA	Final Rule for Emission Durability Procedures for New Light-Duty Vehicles, Light-Duty Trucks and Heavy-Duty Vehicles
2006	EPA	Direct Final Rule for Amendments to Regulations for Heavy-Duty Diesel Engines
2008	EPA	Direct Final Rule for In-Use Testing for Heavy-Duty Diesel Engines and Vehicles: Emission Measurement Accuracy Margins for Portable Emission Measurement Systems and Program Revisions
2009	EPA	Direct Final Rule for Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines: Regulations Requiring Onboard Diagnostic Systems on 2010 and Later Heavy-Duty Engines Used in Highway Applications Over 14,000 Pounds

Year	Agency	Rule/Standard Title
2010	EPA	Direct Final Rule for Revisions to In-Use Testing for Heavy-Duty Diesel Engines and Vehicles; Emissions Measurement and Instrumentation: Not-to-Exceed Emission Standards; and Technical Amendments for Off-Highway Engines
2011	EPA & DOT/NHTSA	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 1
2012	EPA	Final Rule for Nonconformance Penalties for On-Highway Heavy-Duty Diesel Engines
2013	EPA & DOT/NHTSA	Direct Final Rule and Nonroad Technical Amendments for Heavy-Duty Engine and Vehicle
2014	EPA	Final Rule for Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards
2016	EPA & DOT/NHTSA	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2
2020	EPA	Advance Notice of Proposed Rule: Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine Standards
2022	EPA & DOT/NHTSA	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2
2022	EPA	Supplemental Final Rule: Improvements for Heavy-Duty Engine and Vehicle Test Procedures
2021/22	EPA	Final Rule: Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards
2022	EPA	Final Rule and Related Materials for Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards
2023	EPA & DOT/NHTSA	Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 3
2023	EPA	Proposed Rule: Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles

In the transition to a zero-emission economy, we see from the federal government big-picture legislation, regulations, and funding. The next section looks at legislation, executive orders, and rules from the state of California.

3.3 State Actions

California prides itself on being a leader in innovation and change. With the transformation of the transportation sector to zero-emission fleets, California has taken the lead in the nation with developing a regulatory environment and creating a market for zero-emission vehicles. This leadership is seen around the world with California Governors, as leaders of the fifth-largest global economy, traveling to other countries to negotiate climate agreements and take part in climate conferences.

State Legislation

As seen in the federal policy framework for MDHD zero-emission vehicles, at the state level, there is also a combination of legislative action, gubernatorial executive orders, and agency rule making. In California, the move to ZEV began with the passage of Assembly Bill 32 (AB 32), California's Global Warming Solutions Act, in 2006. Passed during Governor Arnold Schwarzenegger's time in office, AB 32 required the level of greenhouse gas emissions in the state to be reduced to 1990 levels by 2020. Therefore, CARB intends to develop regulations to achieve these reductions through the most technologically feasible ways (CARB, 2018). Table 5 shows the policy development for the ZEV transition since 2006 and the passage of AB 32. California met the goal set by AB 32 in 2016, showing what can be done and setting a vision for change in how the transportation system will function in the state. Senate Bill 32 (SB 32) in 2016 followed up on AB 32 with new goals on GHG emission reductions and required any new regulations developed by CARB to be technologically reasonable, cost-effective, and equitable. AB 197 was passed in the same year to provide oversight by the legislature and ensure a balanced approach is maintained as new regulations are developed and stakeholders across the state are impacted (CARB, 2018; Clear Center, 2020).

Table 5. State Legislation Supporting the ZEV Transition, 2006–2023

Year	Bill #	Short Title
2006	AB 32	California Global Warming Solutions Act
2008	SB 375	Sustainable Communities and Climate Protection Act
2012	AB 1532	California Global Warming Solutions Act: Greenhouse Gas Reduction Fund
2012	SB 535	California Global Warming Solutions Act: Disadvantaged Communities
2013	SB 743	Vehicle Miles Traveled Policy
2014	SB 605	Short-Lived Climate Pollutants
2014	SB 1275	Charge Ahead California Initiative
2015	SB 350	Clean Energy and Pollution Reduction Act
2015	AB 1236	Local ordinances: Electric Vehicle Charging Stations
2016	AB 1550	Disadvantaged Communities
2016	SB 32	California Global Warming Solutions Act
2016	AB 197	State Air Resources Board: Greenhouse Gases: Regulations
2017	SB 1	Road Repair and Accountability Act
2017	AB 617	Community Air Protection Program
2018	SB 100	The 100 Percent Clean Energy Act
2018	SB 1000	Land Use: General Plans: Safety and Environmental Justice
2018	AB 2127	Electric Vehicle Charging Infrastructure Assessment: Assessing Charging Needs to Support Zero-Emission Vehicles in 2030 and 2035
2019	SB 676	Transportation Electrification: Electric Vehicles: Grid Integration
2019	SB 210	Heavy-Duty Vehicle Inspection and Maintenance Program
2019	AB 1100	Electric Vehicles: Parking Requirements

Year	Bill #	Short Title
2020	AB 841	Elective Vehicle Infrastructure Training Program and Energy Efficiency Programs
2021	SB 671	Transportation: Clean Freight Corridor Efficiency Assessment
2021	AB 970	Planning and Zoning: Electric Vehicle Charging Stations: Permit Application
2022	AB 2836	Carl Moyer Memorial Air Quality Standards Attainment Program; Vehicle Registration Fees; California Tire Fee
2022	AB 2061	Transportation Electrification: Electric Vehicle Charging Infrastructure
2022	AB 1738	Building Standards: Installation of Electric Vehicle Charging Stations: Existing Buildings
2022	SB 1382	Air Pollution: Clean Cars 4 All Program: Sales and Use Tax Law: Zero Emissions Vehicle Exemption
2022	SB 1251	Governor's Office of Business and Economic Development: Zero-Emission Vehicle Market Development Office: Zero-Emission Vehicle Equity Advocate
2022	SB 372	Medium- and Heavy-Duty Fleet Purchasing Assistance Program: Zero-Emission Vehicles
2022	AB 2700	Transportation Electrification: Electrical Distribution Grid Upgrades
2022	SB 1010	Air Pollution: State Vehicle Fleet
2022	SB 542	Sales and Use Taxes: Exemption: Medium- or Heavy-Duty Zero-Emission Trucks
2023	SB 425	Clean Vehicle Rebate Project: Fuel Cell Electric Pickup Trucks: Battery Electric Pickup Trucks
2023	SB 605	Wave and Tidal Energy

In reviewing all of the policies developed since 2006, it is clear that the ZEV transition is being addressed from many different perspectives. Thirty-four pieces of legislation have been passed to deal with permitting and planning of electric vehicle chargers, new energy generation and transmission improvements, EV purchasing assistance programs, workforce training, and social equity programming. In addition to legislation support by the California Assembly, Senate, and Governor's office, there have also been six executive orders from Governors Brown and Newsom to direct state agencies in the transition to ZEVs.

California Governor Executive Orders

State executive orders function very similarly to federal EOs. The current and most recent governors of California have directed state agencies to implement zero-emission technologies, beginning with EO B-16-12 signed by Governor Jerry Brown. This is seen as the first major step toward the mitigation of greenhouse gas emissions from the MDHD fleet. The most recent EO signed was in 2020, with N-79-20 by Governor Newsom. This EO built upon B-16-12 and set the supply goals seen in vehicle sales.

Table 6. California Governor Executive Orders to Support EV Transition, 2012–2020

Year Signed	EO	Signed By	Short Summary
2012	B-16-12	Brown	Directed state agencies to assist with the development of zero-emission vehicles
2015	B-32-15	Brown	Improve freight efficiency with ZE tech
2018	B-48-18	Brown	Builds on B-16-12 to increase the number of ZEVs and charging stations
2018	B-55-18	Brown	Sets goal to meet carbon neutrality by 2045
2019	N-19-19	Newsom	Created the Climate Investment Framework to provide funding; aligns the state climate goals to transportation spending; make California assets carbon neutral
2020	N-79-20	Newsom	Sets goal for 100% of new vehicle sales in California to be zero-emission by 2035; 100% of MDHD vehicles will be zero-emission by 2045, all drayage by 2035, and 100% of off-road vehicles and equipment ZEV by 2035. Developed a zero-emission vehicle market strategy by January 31, 2021. Accelerated deployment of charging infrastructure. State agencies to update biennial ZEV infrastructure assessment. Set a plan to improve clean transportation, sustainable freight, and transit options by July 15, 2021. Develop a Just Transition Roadmap by July 15, 2021. Transform oil facilities to support communities, labor, public health and the environment. Plan to reduce carbon-intensive fuels. Closure of oil extraction facilities.

California Agency Rules

The legislation and executive orders listed in Tables 5 and 6 have led to the rules, resolutions, and agreements developed primarily by the California Air Resources Board, as shown in Table 7. The Office of Administrative Law provides oversight of any rules developed by state agencies and ensures that they are compliant with the Administrative Procedure Act (APA). This provides the public "with a meaningful opportunity to participate in the adoption of regulations or rules that have the force of law by California state agencies and to ensure the creation of an adequate record for the OAL and judicial review" (OAL, 2023, para. 1).

Table 7. California Regulations and Rules that Support the EV Transition, 2005–2023

Year	Agency	Title
2004	CARB	Airborne Toxic Control Measure for Transport Refrigeration Units (TRU) – Amended in 2010, 2011, 2022
2005	CARB	Airborne Toxic Control Measure to Limit Diesel-Fueled Commercial Motor Vehicle Idling Regulation
2008	CARB	Tractor-Trailer Greenhouse Gas (TTGHG) Regulation
2009	CARB	Statewide Truck and Bus Regulation
2013	CARB	Optional Reduced NOx Standards for Heavy-Duty Vehicles
2013	CARB	Greenhouse Gas Regulations for Medium- and Heavy-Duty Engines and Vehicles, Phase 1
2015	CARB	Sustainable Freight Pathways to Zero and Near-Zero Discussion Document
2016	CARB	Greenhouse Gas Regulations for Medium- and Heavy-Duty Engines and Vehicles, Phase 2
2018	CARB	Innovative Clean Transit Regulation
2020	CARB	Part of the adoption of ACT regulation and set goals for MHDV transition to ZE
2021	CARB	Advanced Clean Trucks Rule
2021	CARB	Revised 2020 Mobile Source Strategy
2022	CARB + 16 States, District of "Columbia" & Province of "Quebec"	MOU to Accelerate Zero-Emission Vehicle Market
2022	CARB	Draft State Implementation Plan (SIP)
2023	CARB	Advanced Clean Fleets Rule

All of this work has led to the timeline seen in Figure 4 for the zero-emission transition to MDHD vehicles. As the timeframe is perceived as very quick for the private sector, with deadlines set in 2024 and 2025, there are a number of exemptions provided, as seen in Table 8. From this figure and table, it is noted that the transition is now. For instance, starting on January 1, 2024, all new drayage vehicles (primarily class 8 trucks that move between the San Pedro ports and warehouses in the IE and locations around the ports) registered or added to the fleet must be zero-emission vehicles. The final goal is for the full drayage fleet operating in the state to be zero emission by 2035. This requirement has an exemption if it is shown that the vehicle type is not yet available. CARB will maintain a list, and fleet owners will be able to purchase an internal combustion engine with the required configurations without first applying for an exemption. The vehicle will have to be reported to the Truck Regulations Upload and Compliance Reporting System (TRUCRS)

(CARB, 2023c). The TRUCRS database is a central compliance tool through which CARB will keep track of all MDHD vehicles. In 2024, CARB has updated its enforcement stance for the Advanced Clean Fleets regulations, delineating a phased approach to compliance. For drayage trucks, enforcement of reporting and registration prohibitions will be on hold until a preemption waiver is granted or deemed unnecessary by the U.S. EPA, with operational restrictions pending for fleets adding internal combustion vehicles after December 31, 2023. High-priority and federal fleets are given a deadline of January 1, 2024, to align with reporting directives and ZEV procurement or to opt for the ZEV Milestone Option, with enforcement contingent on the federal EPA's waiver decision. Similarly, state and local government fleets must comply by the same date, without the need for CARB to seek a waiver.

Figure 4. MDHD ZEV Transition Timeline

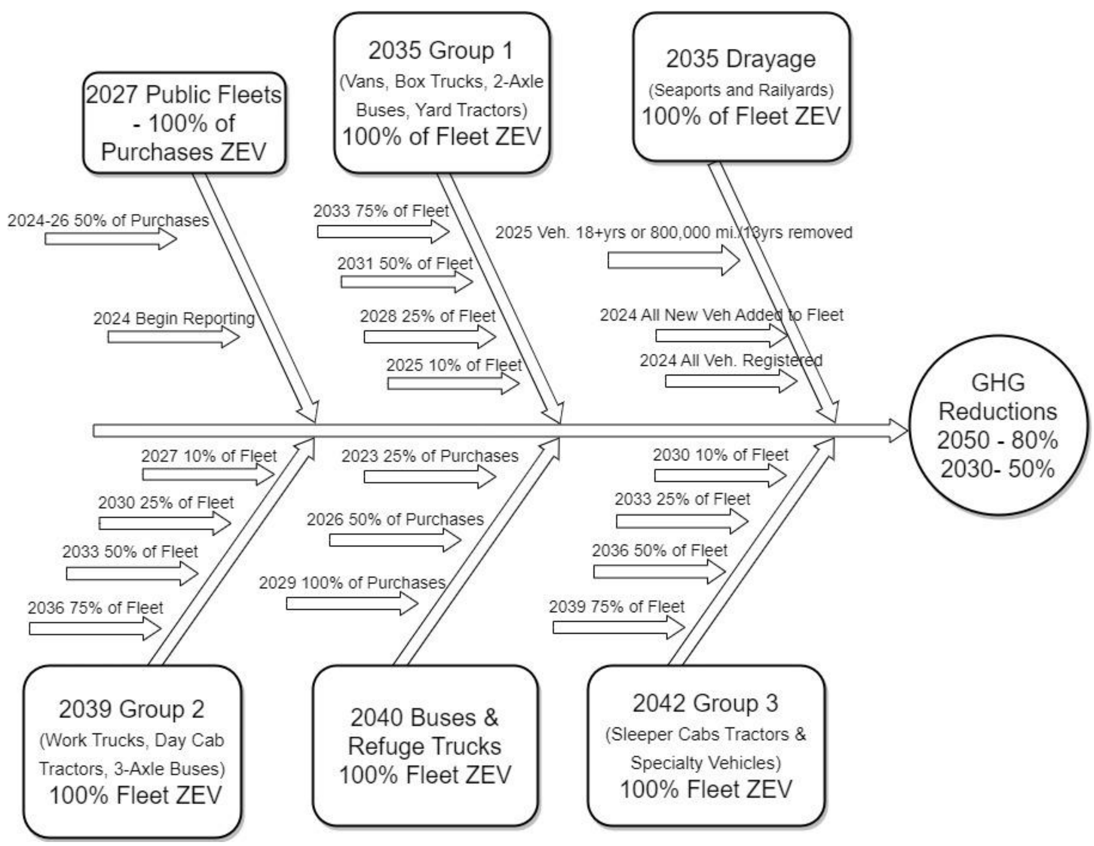


Table 8. Exceptions and Delays for Zero-Emission Vehicle Transition in California

Exception/Delay	Description	Impacted Sectors	Additional Insights
Vehicle Delivery Delay	Arises from unforeseen challenges like supply chain disruptions or manufacturing issues.	Model Year Schedule, ZEV Milestones, Drayage	Governmental bodies may have stricter requirements for timely ZEV procurement.
Infrastructure Delay: Construction	Due to challenges like regulatory hurdles, land acquisition, or weather.	Model Year Schedule, ZEV Milestones, Drayage, State & Local Government	Emphasizes the need for timely infrastructure development.
Infrastructure Delay: Site Electrification	Necessary for places like bus depots or truck stops; delays might stem from grid limitations or permits.	Model Year Schedule, ZEV Milestones, Drayage, State & Local Government	Ensures the effectiveness of ZEV implementation.
ZEV Purchase Exemption	Temporary exemption due to reasons like financial constraints or limited vehicle availability.	Model Year Schedule, ZEV Milestones, State & Local Government	Drayage's absence suggests emphasis on port-related emission reductions.
Daily Usage Exemption	For vehicles with sporadic usage patterns.	Model Year Schedule, ZEV Milestones, State & Local Government	Ensures flexibility while advocating for emission reductions.
Accident/Non-Repairable Vehicle	For instances where a ZEV is severely damaged, and a non-ZEV replacement is used.	Model Year Schedule, ZEV Milestones	Offers a practical solution for unexpected scenarios.
Five-Day Pass	Short-term relief for specific vehicles or operations.	Model Year Schedule, ZEV Milestones	Beneficial for occasional operations not immediately compliant with ZEV standards.
Mutual Aid Provision	For emergencies requiring collaboration between entities.	Model Year Schedule, ZEV Milestones, State & Local Government	Recognizes the need for flexibility during collaborations.
Declared Emergency Event	During official emergencies, like natural disasters, where immediate priority is safety.	Model Year Schedule, ZEV Milestones, State & Local Government	Ensures rapid response during crises.
Backup Vehicle Exemption	For emergency or peak demand vehicles that are not used regularly.	Model Year Schedule, ZEV Milestones	A practical approach for seldom-used vehicles.
Intermittent Snow Removal Vehicles	For seasonally used vehicles focused on safety.	ZEV Milestones, State & Local Government	Immediate ZEV compliance for these vehicles might not be viable.

As seen from this short review of the state system, it is complex, but there are a number of projects funded jointly by the government and business such as JETSI and eTRUC-RHETTA (both are discussed further in the regional actions section). This work is incorporating many different stakeholders and, again, it is a full transformation of how the system has functioned for the past 100 years or so. There is a lot of criticism and worry that it is going to fail, as the technology is still being tested for the MDHD vehicles and the charging infrastructure has not been developed yet. In conducting this research, we spoke to stakeholders who indicated that it is not clear how this transition is going to really work, which is why many governments across the U.S. and the globe are anxious to see California's results. It is a risk, but for anyone observing the current and predicted impacts of global warming and GHG emissions, it is a necessary one. To effectively discuss the transition from the old to the new status quo in freight logistics, it is crucial to examine the specific mechanisms of harm that ZEVs aim to mitigate. ZEVs address key issues such as greenhouse gas emissions, local air pollutants like nitrogen oxides and particulate matter from diesel exhaust, and noise pollution—all of which have significant environmental and public health impacts. By reducing these emissions, ZEVs contribute to mitigating climate change and improving air quality, which is especially critical in urban areas and major freight corridors. This shift not only aligns with global sustainability goals, but also anticipates regulatory trends pushing for lower emissions in transportation logistics.

3.4 Regional Actions

In addition to federal and state institutions and actions, there are regional actors that are highly engaged in the ZEV transition. We looked at seven specific organizations and local utilities for this report. The five organizations are the South Coast Air Quality Management District (AQMD), Southern California Association of Governments (SCAG), San Bernardino Council of Governments (SBCOG), Western Riverside Council of Governments (WRCOG), and JETSI. There are 12 utilities, both shareholder-owned and publicly owned, that service the region. For the sake of this review, we are going to discuss only the largest one, Southern California Edison (SCE).

South Coast Air Quality Management District

South Coast Air Quality Management District (AQMD) was established in 1947. It was one of the first air quality management agencies in the United States. Its purpose is to protect the public health and improve the air quality in areas including Los Angeles, Orange, Riverside, and San Bernardino counties in California. AQMD is committed to promoting cleaner technology, regulating emissions from various sources, enforcing air quality standards, implementing measures to reduce pollution, and ensuring a safer and healthier environment for the people in the region.

The South Coast AQMD's Warehouse Indirect Source Rule (ISR), also known as Rule 2305 or the Warehouse Actions and Investments to Reduce Emissions (WAIRE) program, was adopted in 2021. It mandates large warehouses, specifically those greater than 100,000 square feet, to lower emissions of nitrogen oxide (NOx) and diesel particulate matter (PM 0.03–0.5 μm). The rule, targeting warehouses among the top producers of NOx due to truck traffic and supply chain operations, aims at reducing air pollution in communities affected by these emissions. Compliance can be achieved through on-site measures or equivalent off-site projects, based on a point system that rewards clean operations using ZEVs or near ZEVs for transport. Additionally, the South Coast AQMD is considering extending similar regulations to rail yards and intermodal facilities, focusing on reducing emissions from locomotives, machinery and trucks, with options such as zero-emission technology and operational improvements.

Southern California Association of Governments

The Southern California Association of Governments (SCAG) is the largest metropolitan planning organization in the nation. In 2023, they established the Zero Emission Truck Infrastructure (ZETI) study that aims to establish a network of zero-emission truck charging and fueling stations in Southern California. This initiative seeks to improve air quality, reduce greenhouse gas emissions, and support the goods movement industry while aligning with state and federal environmental goals. The study's objectives include developing a regional infrastructure plan, conducting a truck market study to project energy demands, mapping proposed station locations in phases, incorporating existing sector plans, engaging with various stakeholders, and planning for specific site locations. The findings will be integrated into the Electric Truck Research and Utilization Center (eTRUC) Project, which is part of the CEC Research Hub for Electric Technologies in Truck Applications (RHETTA) Program led by the Electric Power Research Institute (EPRI). The ZETI is part of SCAG's broader strategy for regional planning, emphasizing collaboration with diverse partners.

SCAG also partnered with Caltrans on the EV Oasis South project in 2023, funded by the Trade Corridor Enhancement Program TCEP, to install microgrid-enabled charging equipment for heavy-duty trucks at TravelCenters of America (TA) and Petro locations in Southern California. The project aims to charge up to 82 trucks daily in the first five years, with capacity increasing as demand grows. This initiative will enhance charging accessibility for MDHDVs, contributing to GHG reduction, improved air quality, and public health.

SCAG has collaborated with the Mobile Source Air Pollution Reduction Review Committee (MSRC) to create the Last Mile Freight Program (LMFP), which operates in two phases. In Phase 1, selected projects focusing on the commercial deployment of zero-emission or near-zero-emission heavy and medium-duty trucks, including equipment and infrastructure, are in implementation. This phase involves 26 projects funded with $16.8 million, engaging participants from small independent operators to large companies such as Sysco Corporation, PepsiCo, Inc., and Penske. Phase 2 aims to expand these efforts by working with public and private sector stakeholders to deploy innovative technologies demonstrated by leading last-mile delivery companies, especially in e-commerce. The LMFP is designed to facilitate the shift to zero-emission technologies and foster public-private partnerships, improving understanding of new technologies. Its primary goals are to enhance public air quality and demonstrate industry return on investment to scale these technologies further.

Another notable SCAG plan is to invest $5 billion in freight arterial operations and maintenance, adapting to changes brought by heavier-battery electric freight vehicles. This investment addresses increased roadway degradation, particularly on arterials serving industrial and retail locations, intensified by last-mile deliveries. The focus is also on enhancing connections between freight corridors and key last-mile access arterials that link to major industrial facilities such as seaports, rail yards, and distribution centers.

San Bernardino Council of Governments

SBCTA has initiated efforts to support the electrification of buses in compliance with the California Air Resource Board's Innovative Clean Transit (ICT) regulation. This includes preparing the Zero Emission Bus (ZEB) Study Master Plan and the Final Countywide ZEB Rollout Plan (2020) to guide transit operators in transitioning to zero-emission fleets by 2040. As of December 2022, this effort involved replacing 155 fixed route buses and 74 paratransit vehicles across the county. The transition to zero-emission buses, which includes both electric and hydrogen-based technologies, presents operational challenges due to limitations in vehicle range affected by weather, terrain, and driving habits. Despite these hurdles, transit operators are exploring new fueling options and adapting their operations. For instance, Victor Valley Transit Authority (VVTA) introduced its first seven battery-electric buses in 2019, and Omnitrans is integrating alternative-fueled vehicles and has prepared its first Climate Action Capital Plan (FY 2022/2023) to outline its compliance strategy with both state and federal regulations.

In the framework of the San Bernardino County Transportation Authority (SBCTA) Zero-Emission Vehicle Readiness and Implementation Plan (2019), Implementation Goal 4 addresses the affordability and accessibility of Electric Vehicle Infrastructure (EVI). The goal seeks to diminish the financial and procedural barriers to EVI installation for a diverse range of stakeholders, including business owners, fleet managers, and multi-unit dwelling owners, thereby fostering the proliferation of low-cost fueling options.

The plan delineates several key strategies to this end:

- Pursuit of grant funding opportunities through programs like the Carl Moyer program, HVIP, AVFVTP, CMAQ, and FAST Act, alongside Clean Energy Loan Guarantees.

- Exploration of various incentive programs such as the California Vehicle Rebate Program (CVRP), the California Hybrid and Zero Emission Truck and Bus Voucher Incentive Project, the Enhanced Fleet Modernization Program, the Goods Movement Emission Reduction Program, and the Place Program.

- Maximization of benefits from the Low Carbon Fuel Standard (LCFS) credits through accumulation and monetization, with consideration of utilizing programs such as SCE's Charge Ready Program and Colton Electric's funding for Level 1 and Level 2 Electric Vehicle Charging Stations (EVCS) at nonresidential sites.

- Engagement with local initiatives like Rancho Cucamonga's Level 2 Charging Program, which offers rebates for residential Level 2 charger installation, and Colton Electric's Charger Incentive Program, which provides financial incentives for commercial charger installation.

The plan outlines metrics for success, including the number of charging stations installed and the amount of funding awarded. Reporting on these metrics will be conducted at intervals varying from quarterly to annual to entities like the CARB. The outlined strategies indicate SBCTA's approach to reducing economic impediments to EVI deployment, which is critical for the transition towards a fleet composed entirely of zero-emission vehicles.

Western Riverside Council of Governments

The Western Riverside Council of Governments (WRCOG) has been promoting the adoption of MDHDVs in the region through a variety of initiatives. In terms of policy and planning, WRCOG has incorporated goals and strategies in its Regional Transportation Plan (RTP) to encourage MDHDV adoption. The 2020 RTP aims for a 25% transition of the region's MDHDV fleet to electric by 2035. Additionally, WRCOG developed a Zero Emission Vehicle Action Plan in 2021 that outlines strategies to accelerate ZEV deployment, including MDHDVs. This plan focuses on funding, infrastructure development, workforce development, and public outreach.

WRCOG has been instrumental in expanding electric vehicle infrastructure. They partnered with the California Energy Commission for a project that aims to install 100 new fast-charging stations for MDHDVs along key freight corridors. This initiative addresses a major barrier to MDHDV adoption: the lack of adequate charging infrastructure. Furthermore, through its Clean Transportation Program, WRCOG provides funding for projects that reduce pollution and greenhouse gas emissions from transportation sources, including via the development of electric truck charging stations and demonstration projects for electric school buses.

JETSI

The Joint Electric Truck Scaling Initiative (JETSI) project is a public-private initiative funded by the California Air Resources Board, State of California Energy Commission, Clean Transportation Funding from the Mobile Source Air Pollution Reduction Review Committee (MSRC), Daimler Truck North America, NFI Industries, South Coast AQMD, Schneider, and Volvo. NFI Industries' operations in Southern California are closely tied to the IE region. NFI operates regional-haul and drayage routes, moving 40-foot trailers of goods primarily under 150 miles round-trip. These routes include servicing the Ports of Los Angeles and Long Beach and connections between logistics and warehouse facilities, making them highly relevant to the IE's extensive logistics and distribution network.

NFI's facility in Ontario (California) is pivotal for the JETSI project. Chosen for its proximity to a significant number of drayage customers, it plays a central role in Southern California's freight transportation network. The facility is equipped with 30 Freightliner eCascadia and 20 Volvo VNR Electric Class 8 trucks, and its charging infrastructure includes 19 dual-port 350 kW chargers (38 ports), 1 MW solar power, and 5 MWh battery energy storage. This setup underscores the region's shift towards sustainable logistics practices.

These areas suffer from emissions and pollution due to heavy truck traffic and goods movement. State guidelines such as AB 617 and SB 535 target these communities for air quality improvements. By using Battery Electric Trucks (BETs), the JETSI project aims to reduce tailpipe emissions, benefiting the air quality and health of residents in the IE.

Utilities

Southern California Edison's (SCE) Charge Ready Program, while addressing a broad range of EV needs, places particular emphasis on electrifying MDHDVs such as delivery trucks, buses, and construction vehicles, which are substantial contributors to greenhouse gas emissions. Transitioning these vehicles to electric power is crucial for cleaner air and a sustainable future.

This program is tailored for businesses with MDHDV fleets and offers two main advantages. Firstly, it provides infrastructure funding, covering a significant portion of the costs for installing high-powered charging stations suitable for MDHDVs. These stations can deliver megawatts of electricity

> "I think initially, most of the people are kind of transitioning to newer equipment that can be on their registry for a while, but I think in the next three or four years you'll see where trucks kind of mile out, or hit that 800,000 mile limit, or they hit their year limit and they're a smaller 10 and under size carrier that's where the struggle is going to come in, because I don't know the by then three or four years from now we're going to be in a better place when it comes to the cost of the zero emission trucks or just the drayage side, that goes into trying to get through the process, not only buying the vehicle, but the infrastructure piece and then eventually what happens when we don't have enough money."
>
> *Public Sector*

rapidly, minimizing charging downtime for heavy-duty vehicles. Secondly, the program offers special charging rates, partnering with participants to create customized charging plans that optimize energy use and cost, ensuring economic feasibility for fleet operators.

The advantages of MDHDV electrification go beyond cost reduction. Charge Ready Transport aids businesses in reducing emissions, as electric trucks and buses produce zero tailpipe emissions, thus contributing to cleaner air and public health improvement. It also helps enhance brand image, as companies adopting innovative technology and environmental responsibility can gain a competitive edge and appeal to sustainability-conscious customers. Furthermore, EVs typically provide a smoother and quieter operation, which can reduce driver fatigue and possibly increase job satisfaction. Charge Ready Transport also plays a significant role in charging infrastructure development, contributing to the establishment of a robust network of high-power charging stations throughout Southern California. This development paves the way for more businesses to adopt MDHDVs, fostering a broader movement towards fleet electrification.

In conclusion, Charge Ready Transport within the broader Charge Ready Program plays a crucial role in accelerating the transition towards a cleaner transportation future. By providing financial support, technical expertise, and infrastructure development for MHDV charging, SCE empowers businesses to make the switch to electric power, paving the way for cleaner air, reduced emissions, and a more sustainable Southern California.

3.5 Public Sector Interviewees Standpoint

After conducting interviews with eight interviewees from the public sector some common thematic subjects became obvious. Firstly, the aspect of awareness and knowledge emerged as a critical factor. A segment of the interviewees demonstrated a robust grasp of the nuances involved in California's EV transition, whereas another subset acknowledged a deficit in their understanding, thereby underscoring an exigency for enhanced informational dissemination and awareness amplification.

Respondents consistently underscored the well-developed charging infrastructure, highlighting the challenges involved in charging time and logistical feasibility. This factor was identified as a cornerstone in the successful implementation of the EV transition, necessitating a strategic and infrastructure overhaul. In the realm of training and education, a dichotomy was evident. Some respondents referred to proactive engagement in ongoing training initiatives, signifying a forward-leaning approach to capacity building. Conversely, the absence of such initiatives was noted by others, pointing to a disparity in educational outreach and skill development.

The interviews also expanded on the financial aspects of the transition. There was a unanimous emphasis on the imperative of securing financial support and funding. This aspect was deemed crucial for mitigating the financial burden and catalyzing the transition process. Support and collaboration were other pivotal themes. A multifaceted support system encompassing technological, infrastructural, and educational assistance was viewed as indispensable. The emphasis on collaborative efforts, particularly in garnering support, underscored the attitude of collective efficacy and shared responsibility in the transitional journey. In the domain of policy and regulation, respondents highlighted the consequential role of regulatory frameworks. The data suggested that policies and regulations are not mere backdrop elements, but active shapers of strategic approaches and opinions regarding the EV transition.

Lastly, the interviews reflected a balanced perspective on challenges and opportunities. While infrastructural constraints, technological hurdles, and awareness gaps were acknowledged as significant challenges, an undercurrent of optimism was obvious. Respondents perceived these challenges as coexisting with opportunities for innovation, growth, and sustainable development.

3.6 Section Takeaways

California has a very robust regulatory framework for the transition to zero-emission vehicles. With a combination of federal policy, state policy, and regional programming, there are many initiatives and programs to develop the market for MDHD ZEVs. As we see in this section, there are 23 pieces of federal legislation since 1970 that address environmental, energy, and transportation issues; 15 presidential executive orders since 1993 emphasizing the federal implementation of legislation, clean vehicle technologies, and highlighting social equity principles; and the U.S. Environmental Protection Agency (EPA) and Department of Transportation have developed 25 rules and standards since 1976. At the state level, the legislature have created 34 pieces of specific legislation, starting with AB32 in 2006. There have been six executive orders signed by the past two governors, and 15 rules and standards developed by CARB since 2004. In addition, there are public-private initiatives such as JETSI and e-TRUC-RHETTA and multiple programs at the regional level with AQMD, SCAG, SBCOG, WRCOG, and SCE. It is a highly detailed and complex initiative, showing the government innovation to completely change how the transportation sector functions. For government policy to support innovation and change in private sector activities, there needs to be:

> … a portfolio of innovation policies that set clear mandated targets that can push firms toward technological change; policies that assist the firms in developing and improving their technical capacity; policies that emphasize the development and improvement of infrastructures and business platforms; policies that promote a quality workforce; and policies that create favorable business environments (Patanakul & Pinto, 2014, p. 104).

These are all occurring with the current policy framework.

The downside of this complex system is that there is a high level of uncertainty. If we look at theories of how businesses change and implement new innovations, there are three considerations: the willingness to change, the capacity to change, and the opportunity to change. Of the surveys completed for this project, most indicated that businesses are willing to change. Surveys show most businesses in the state see the need to move to zero-emission vehicles. Issues arise when looking at capacity and opportunity. A large component of success for the innovative transformation of this sector hinges on addressing the capacity and opportunity questions crucial for implementation. Additionally, the levels of uncertainty surrounding this transition need further exploration in order to mitigate risks and prepare for potential challenges. Addressing these elements will provide a foundation for the following discussion on the necessary regulatory, financial, and technological frameworks that are pivotal for supporting this sector's transformation.

Part III: Transportation and Urban Systems Analysis

4. Transportation and Urban System

4.1 Introduction

This section delves into an intricate analysis of traffic OD patterns, dwell counts, and the spatial distribution of businesses and utilities in the IE, using Streetlight Data from 2021. The focus is on understanding the movements and stationary behaviors of MDHDVs across six subregions of the IE, namely North, West, East, South, South-Center, and North-Center. Through a series of detailed figures and maps, we examine bidirectional trips, aggregate vehicle movements, and the concentration of MDHDVs in specific areas, as well as the impact of these patterns on parking needs and land use. Key insights include the identification of high-density traffic zones, the prevalence of various types of trips within the region, to and from a 77-mile buffer zone, and beyond the 77-mile buffer zone, and the dwell times of these vehicles. This analysis not only illustrates the current state of vehicular traffic and parking in the IE, but also provides a foundation for planning future infrastructure, particularly in relation to the electrification of MDHDVs. Additionally, the exploration of business and land use patterns through a unique indexing method offers a comprehensive understanding of the regional economic landscape, highlighting areas with a high concentration of businesses.

The present research is unique compared to existing databases that planners and others may be using. Our new indexing method brings a novel approach to categorizing and analyzing land use, and geographic and business concentration, providing insights that were previously unattainable. This method integrates various data points, allowing for a more detailed and accurate representation of the economic landscape. By framing the information within the context of its origin and significance, we offer a robust framework that enhances the reader's understanding of regional dynamics and supports more effective decision-making in urban planning and infrastructure development.

4.2 Traffic Origin-Destination Analysis

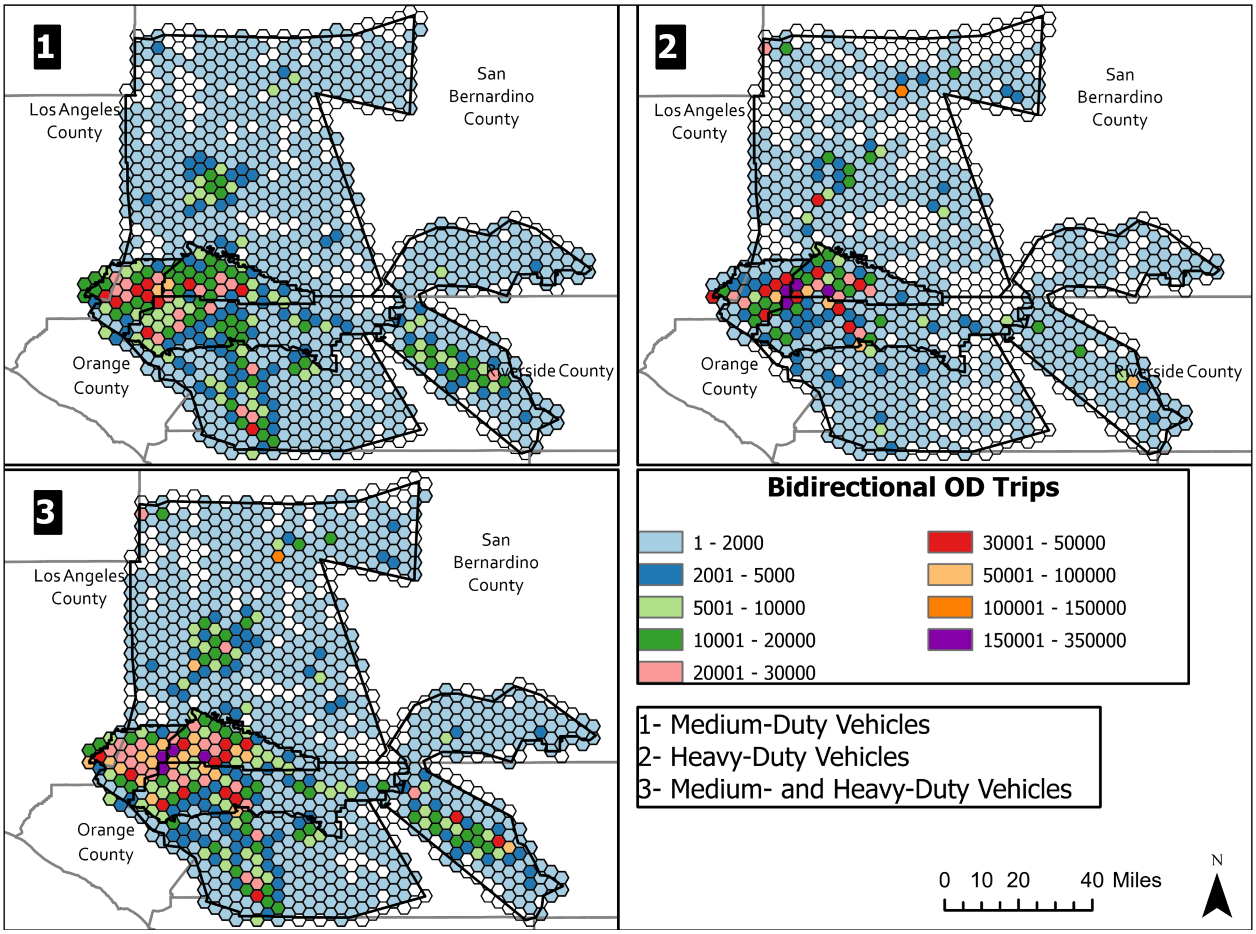
In this section, StL data was utilized to analyze the origin and destination (OD) bidirectional trips in the six subregions of the IE: North (N), West (W), East (E), South (S), South-Center (SC), and North-Center (NC). These subregions correspond to the designated areas on all maps used in this study. Figures 6–8 provide a detailed breakdown of traffic patterns, showing the aggregate number of trips within the region and its subregions, and trips that extend beyond the 77-mile buffer zone to and from the region. This analysis is crucial for understanding the movement of goods and people, identifying key transportation corridors, and assessing the capacity and efficiency of current infrastructure. By examining these traffic patterns we can better evaluate the impacts of transportation logistics on regional planning and the potential benefits of transitioning to zero-emission vehicles. This contextual understanding sets the stage for interpreting the figures and drawing meaningful conclusions about the transportation dynamics within the IE.

Each figure consists of three maps, each representing the density of bidirectional OD trips for different classes of vehicles within the IE. Each map is categorized by the type of vehicle: (1) MDVs, (2) HDVs, and (3) a combined analysis of MDHDVs. The hexagonal grid cells are color-coded based on number of trips, indicating the volume of trips ranging from 0–2,000 (lowest OD trips in light blue) to 150,001–350,000 (highest OD trips in purple). All the maps show the yearly OD patterns in the IE.

Total Trips to and from the Inland Empire

Figure 5 provides the cumulative vehicle movement within and from the outside of the IE, by subregion. Map 1 shows that there are a high number of bidirectional trips, mostly in the W, NC, and SC subregions, with some areas exceeding 150,000 trips. Other subregions have MDV trip traffic with less density, with more areas experiencing trips between the range of 1 and 20,000. In Map 2, there is a concentration of HDV trips in the W and NC subregions and in a limited area of the N subregion. Overall trips are shown in Map 3, where both MDV and HDV trips are summed, illustrating that the W, NC, and SC subregions have the highest truck trips. Also, in areas within the N subregion, there are more than 100,000 trips, but most of the areas have around 2,000 trips. The S and E subregions also have moderate numbers of trips with respect to the E, SC, and NC, with some areas exceeding 30,000 trips.

Figure 5. Aggregate Bidirectional OD Trips for Total MDHDV Traffic
to and from the Inland Empire, 2021

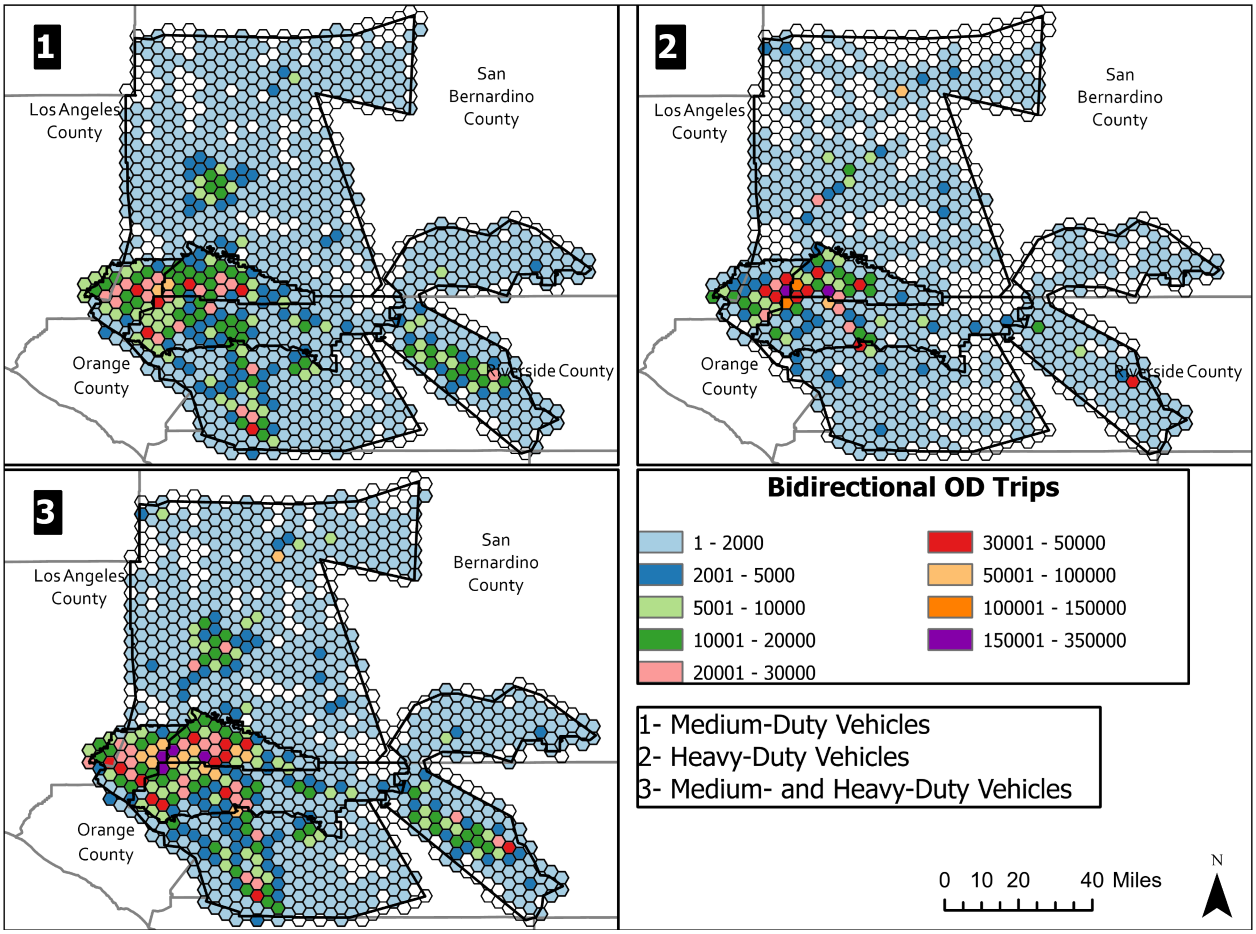


Source: Streetlight Data, 2021

Analyzing Bidirectional Origin-Destination Traffic Patterns for MDHDVs within the Inland Empire

Figure 6 depicts the bidirectional OD trips within the IE. This data provides the concentrations of regional short-haul trips by truck classification. Map 1 shows the bidirectional OD trips for MDVs within the IE. The subregions with the highest number of trips are the West (W), North-Center (NC), and South-Center (SC). The OD traffic in the South (S) and East subregions is less dense than the other above-mentioned subregions. The North (N) subregion has the lowest traffic for MDVs within the IE. On the other hand, Map 2 shows the bidirectional OD trips for HDVs. The W and the NC subregions experience the highest density of trips, followed by the SC subregion. In Map 3, the bidirectional OD trips for both MDVs and HDVs are shown. The heaviest truck traffic is found in tessellations located in the W, SC, and NC subregions, followed by the central part of the N subregion and the southern part of the E subregion.

Figure 6. Mapping of Bidirectional Origin-Destination Trips for Medium- and Heavy-Duty Vehicles within the Inland Empire, 2021

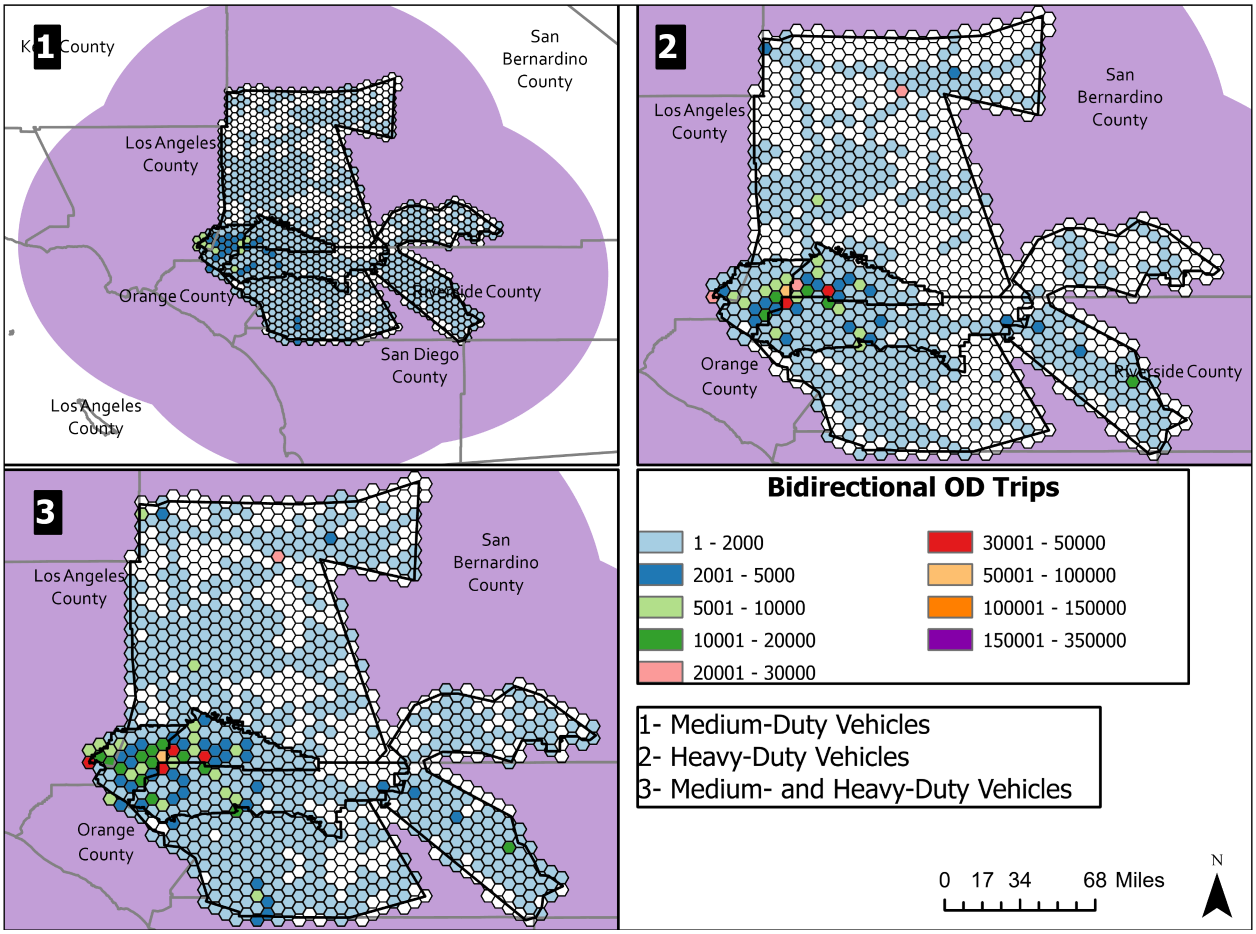


Source: Streetlight Data 2021

Analyzing Bidirectional Origin-Destination Traffic Patterns for MDHDV Trips Between the Buffer Zone and the Inland Empire

Figure 7 provides the inter-regional flows between the IE and its 77-mile buffer zone. This figure depicts the regional short-haul trips within the Southern California region. In comparison to earlier maps focusing solely on internal traffic, these maps illustrate a significantly lower number of trips for inter-regional trips. In Map 1, we can see the highest MDV trips are in the W, NC and SC subregions. All other areas were in the range of 1–2000 MDV trips range. The highest HDV traffic is noted in the NC subregion, with recordings of 50,000 trips. The W subregion ranks the second highest number of HDV trips. Of specific note is Barstow in the N subregion has significantly higher HDV traffic with respect to all other parts of the N subregion—up to 30,000 average trips.

Figure 7. Mapping of Bidirectional Origin-Destination Trips for Medium- and Heavy-Duty Vehicle Trips Between the Buffer Zone and the Inland Empire, 2021

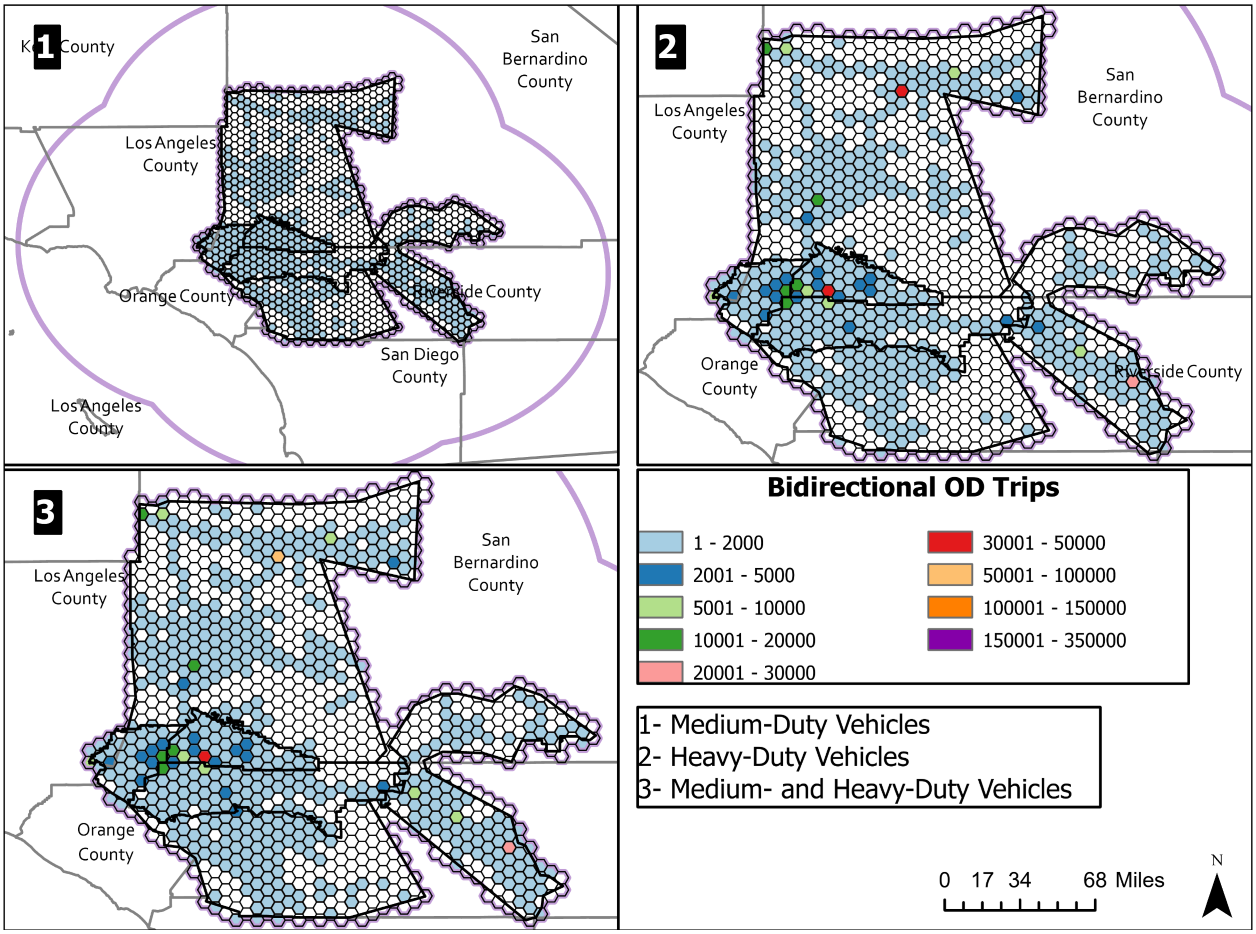


Source: Streetlight Data, 2021

Trips Outside the Buffer to and from the Inland Empire

Figure 8 shows that HDV traffic dominates the LH trips. Map 1 shows that all regions have low MDV traffic. Map 2 shows that HDV traffic is higher in the NC subregion and some parts of the E subregion. It is also notable that in the N subregion, Barstow has up to 50,000 trips. The same trend is also reflected in the total MDV and HDV trips combined on Map 3.

Figure 8. Mapping of Bidirectional Origin-Destination Trips for Medium- and Heavy-Duty Vehicles Trips Outside the Buffer to and from the Inland Empire, 2021



Source: Streetlight Data 2021

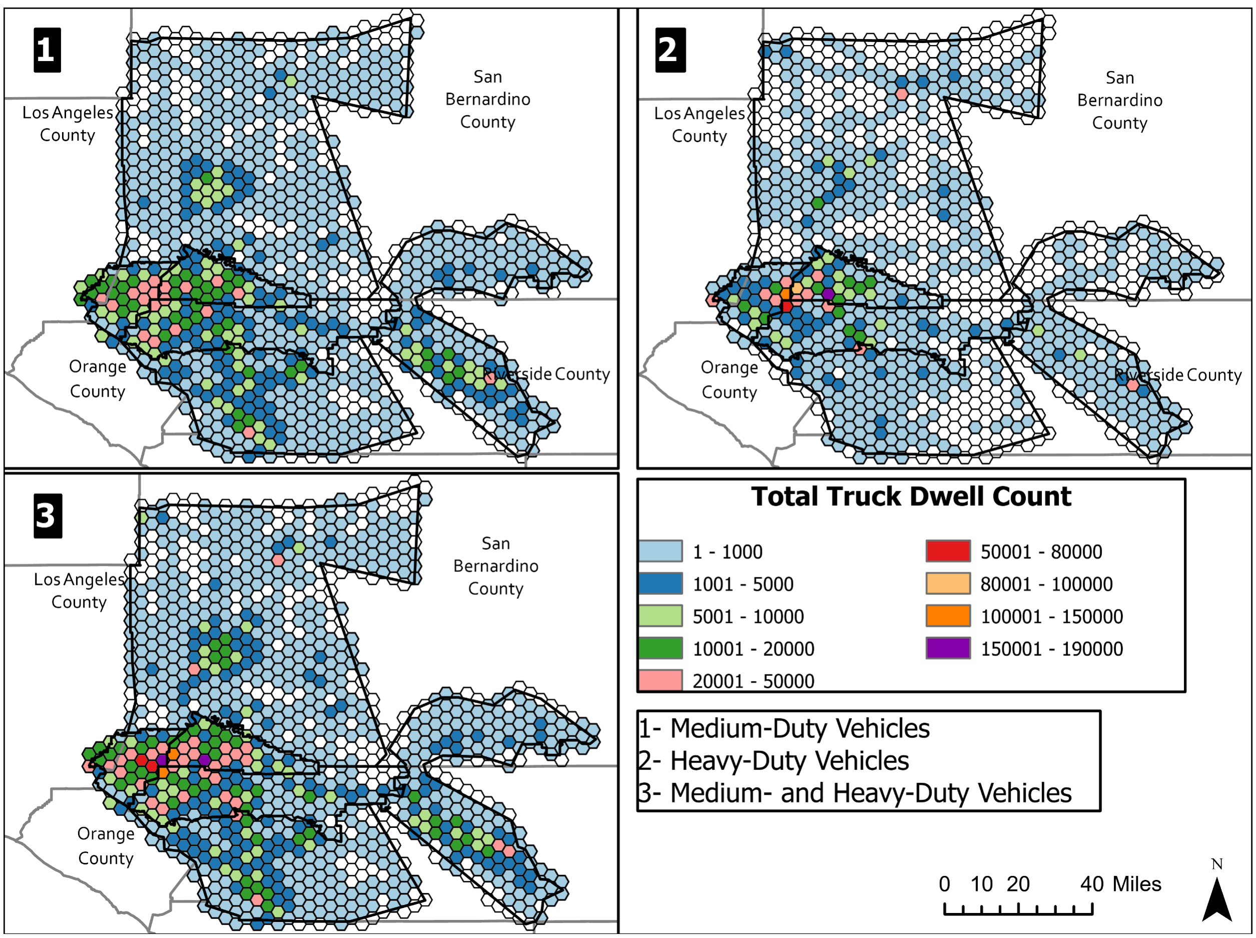
4.3 Fleet Dwell Count and Time

MDHDVs' Dwell Count in the Inland Empire

The distribution of dwell counts, indicating where MDHDVs stop within the region, is crucial for planning the transition to MDHD EVs. These counts help identify high-demand areas for charging infrastructure, ensuring that EV charging stations are strategically placed for maximum usage. Additionally, dwell counts reveal key logistical hubs and rest areas, guiding infrastructure development to support efficient and effective EV operations. Figures 8–10 provide the number of vehicles and where they are resting in the IE, the average dwell time by location, and the length of time spent resting by vehicle class. The color scheme represents the range of dwell counts, starting from light blue for the lowest range (1–1,000) to dark purple for the highest range (150,001–190,000).

Map 1 in Figure 9 shows the dwell count of MDVs. The highest number of MDVs dwelling are in the W and the NC subregions, with up to 50,000 trucks in certain areas in those subregions. The SC subregion also has concentrations of MDVs, with four areas ranging between 20,000 and 50,000 MDVs. Following these three are the S, E, and N subregions with a notable number of MDVs dwelling, but with less density and count. Map 2 shows the highest number of HDVs are in the W and NC subregions, with a slight difference in some areas, like the purple tessellation in the NC having more than 150,000 HDVs dwelling in 2021. The SC subregion also has a distinctive number of HDVs dwelling in two unique areas: one exceeding 50,000 HDVs and the other exceeding 20,000 HDVs. Also, in the N subregion, specifically in Barstow City (the dark pink tessellation), more than 20,000 HDVs dwelled in 2021. The third map shows the total number of MDHDVs dwelled in 2021, where the E and NC had the highest dwelling count followed by the SC, the S, the E, and the N.

Figure 9. MDHDV Dwell Count by Location in the Inland Empire, 2021

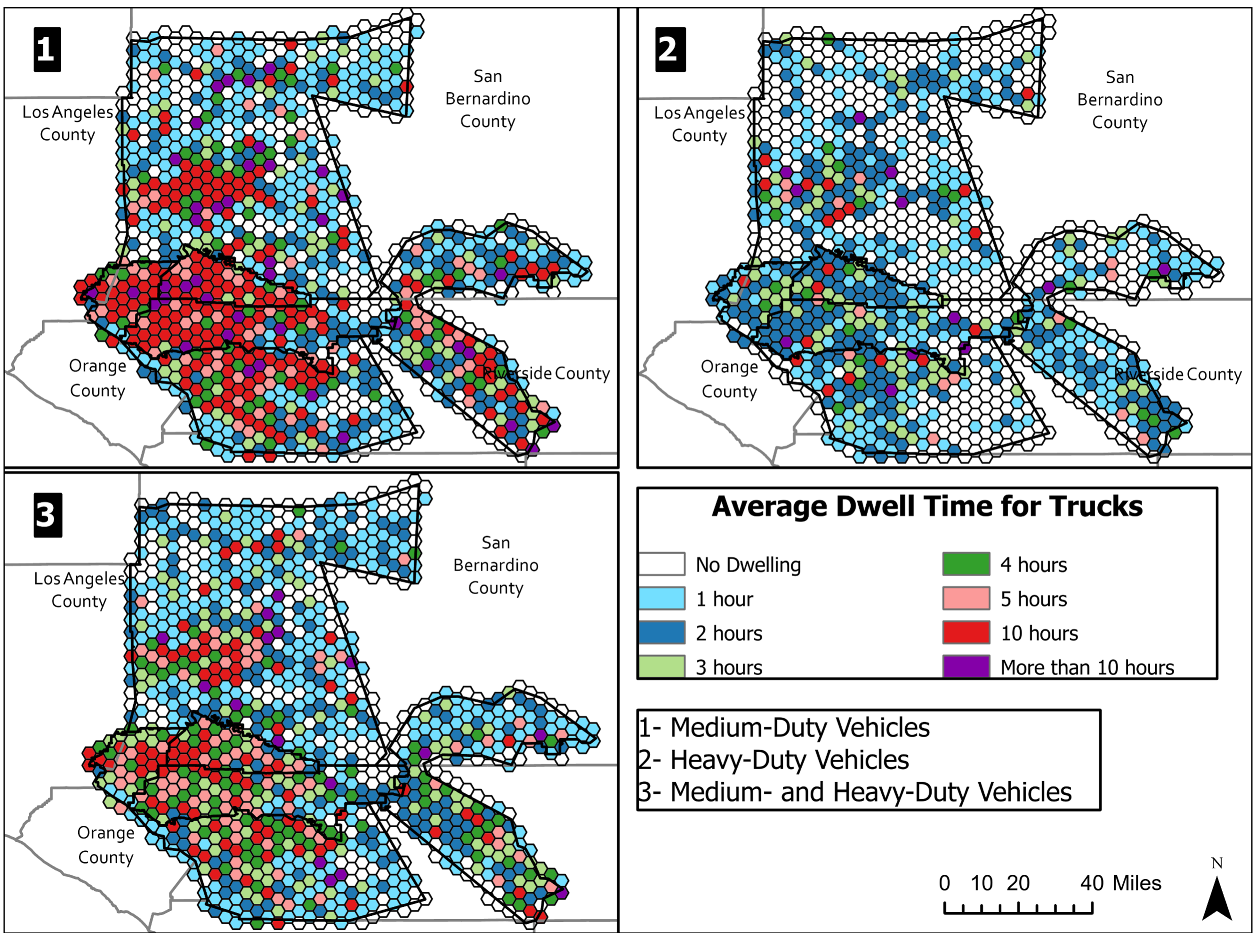


Source: Streetlight Data 2021

MDHDVs' Average Dwell Time in the Inland Empire

Figure 9 provides a detailed analysis of MDHDV operations in the IE, focusing on the average dwell times for these vehicles in 2021. The visualization categorizes dwell counts into different ranges, highlighting areas where MDHDVs remain stationary for varying durations. Map 1 shows the dwell counts for medium-duty vehicles, illustrating significant stopping times in specific areas. Map 2 displays the dwell counts for heavy-duty vehicles, focusing on regions where these larger vehicles are stationary. Map 3 combines data for both MD and HD vehicles, offering a comprehensive view of all MDHDV activity within the IE. The maps reveal that certain areas, particularly in the western part of the IE near Orange and Los Angeles counties, exhibit higher dwell times.

Figure 10. MDHDVs' Average Dwell Time, 2021



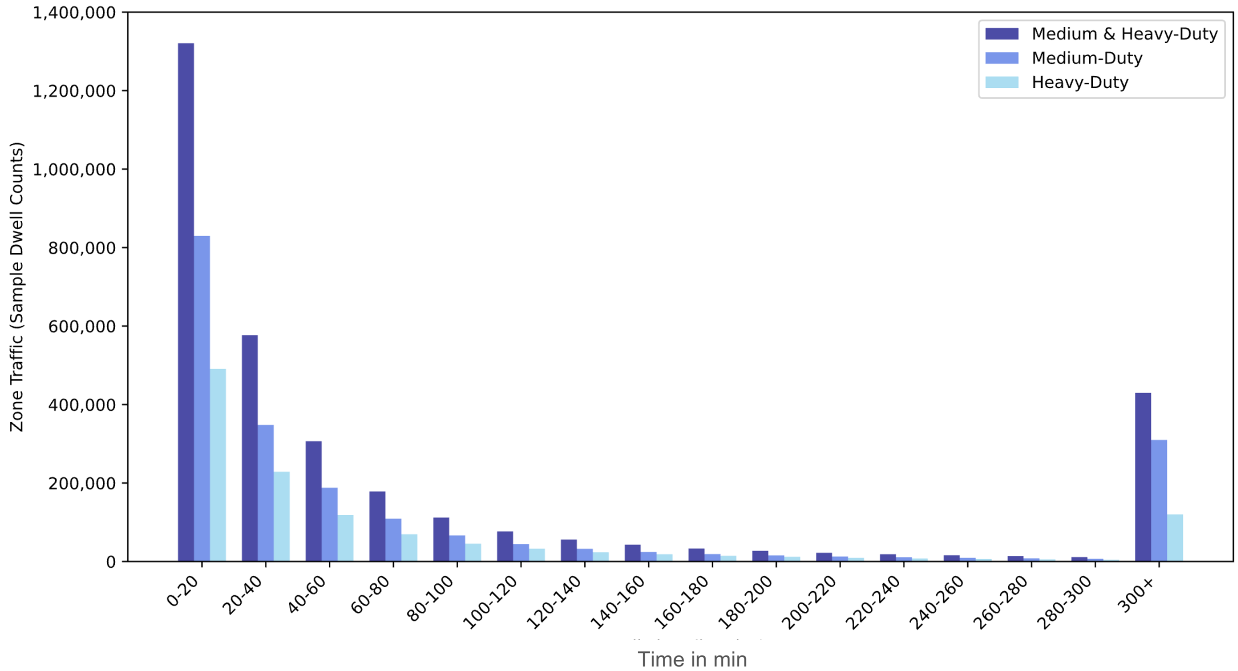
Source: Streetlight Data 2021

Map 1 in Figure 10 shows the average dwell time of MDVs. The average dwell time is 10 hours in the E, NC, SC, and S subregions. Map 2 shows that the HDVs' average dwell time is significantly lower than the MDVs for all subregions, with some exceptions as reflected in the red and purple areas. When aggregating the MDVs and HDVs in Map 3, in the majority of the E, NC, SC, and S subregions, the average dwell time exceeds three hours.

Impact of Dwell Time and County on Charging Strategies for Medium- and Heavy-Duty Vehicles in the Inland Empire

The electrification strategy for MDHDVs in the IE must consider vehicular dwell time. Shorter dwell times necessitate opportunity charging networks, while longer periods require stations for extended charging. Figure 11 illustrates dwell time patterns for MDVs and HDVs in 2021. Short stops were the highest for both MD and HD trucks, suggesting both made frequent stops of short duration. This pattern indicates that MDVs are likely engaged in delivery or regional services, which necessitates frequent but brief stops. For these vehicles, opportunity charging solutions would be ideal to ensure they can recharge during their regular operational stops without significant disruption to their service. The presence of higher dwell times implies that these vehicles often have extended periods of inactivity, due to LH operations that involve regulated rest periods. For HDVs, traditional charging stations, possibly with overnight charging capabilities, would be beneficial to utilize these longer dwell periods effectively. When aggregating the data for both MDVs and HDVs, the graph shows a considerable number of instances across all dwell time categories, with notable peaks at both the short (0–20 minutes) and long (300+ minutes) extremes. This suggests a diverse range of operational behaviors that require a multi-faceted approach to charging infrastructure development.

Figure 11. Dwell Time Distribution for Medium-Duty, Heavy-Duty, and Combined MDHDV Categories, 2021



Source: Streetlight Data 2021

4.4 Transportation and Warehousing Facilities in the Inland Empire

An index was developed to capture both the number of businesses and the size of the facilities. This index merges the count of businesses with their average facility square footage, yielding a composite measure that conveys the density and operational scale of business entities in the region. By assigning multipliers to categorized square footage ranges, the index provides a granular yet comprehensive view of the business landscape.

To construct the index, each business entity was first categorized based on the average square footage of its facility. These categories were predefined ranges with corresponding index multipliers, assigned to reflect the relative scale of the facility's square footage. The multipliers increase with the size of the square footage range, thereby ensuring that larger facilities contribute more heavily to the index. This scaling is grounded in the assumption that larger facilities typically have a bigger operation, hence more MDHDVs.

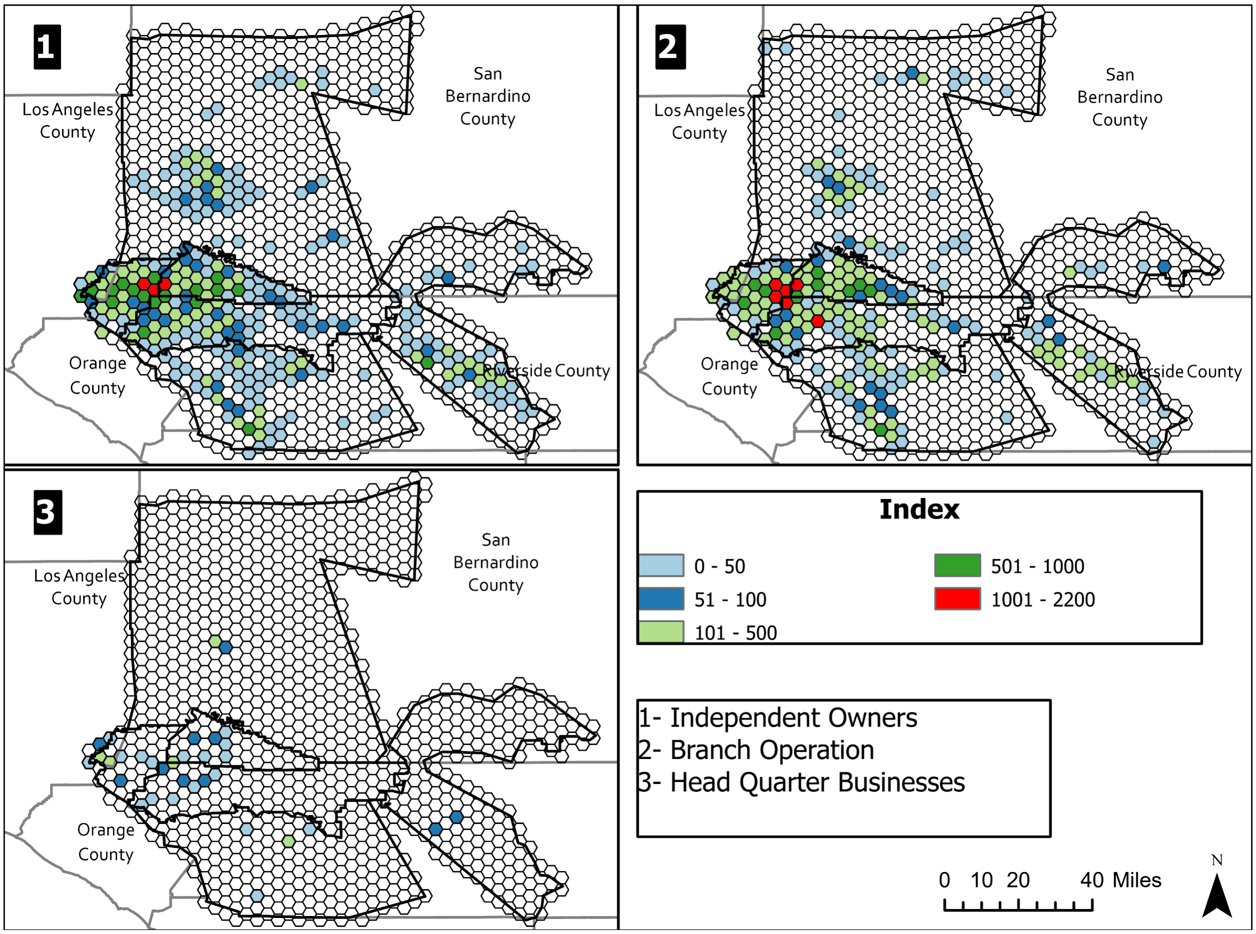
The square footage ranges and their associated multipliers were as follows:

- 1–1,499 sq. ft: assigned a multiplier of 0.75
- 1,500–2,499 sq. ft: assigned a multiplier of 2

- 2,500–4,999 sq. ft: assigned a multiplier of 3.75
- 5,000–9,999 sq. ft: assigned a multiplier of 7.5
- 10,000–19,999 sq. ft: assigned a multiplier of 15
- 20,000–39,999 sq. ft: assigned a multiplier of 25
- 40,000–99,999 sq. ft: assigned a multiplier of 70
- 100,000+ sq. ft: assigned a multiplier of 100.

Each business within a hexagonal area on the map was then assigned the appropriate multiplier based on its square footage range. The index value for each hexagon was calculated by summing the products of the number of businesses and their corresponding multipliers within that hexagon. The result is a set of index values that integrate both the density of businesses and the magnitude of their operational spaces. This method allows for a visual and quantitative comparison across different business types and geographical areas, offering valuable insights into regional truck traffic movement.

Figure 12. Index Reflecting the Independent Owners, Branch Operations, and Headquarter Businesses in the Inland Empire



Source: ESRI Data Axle, 2021

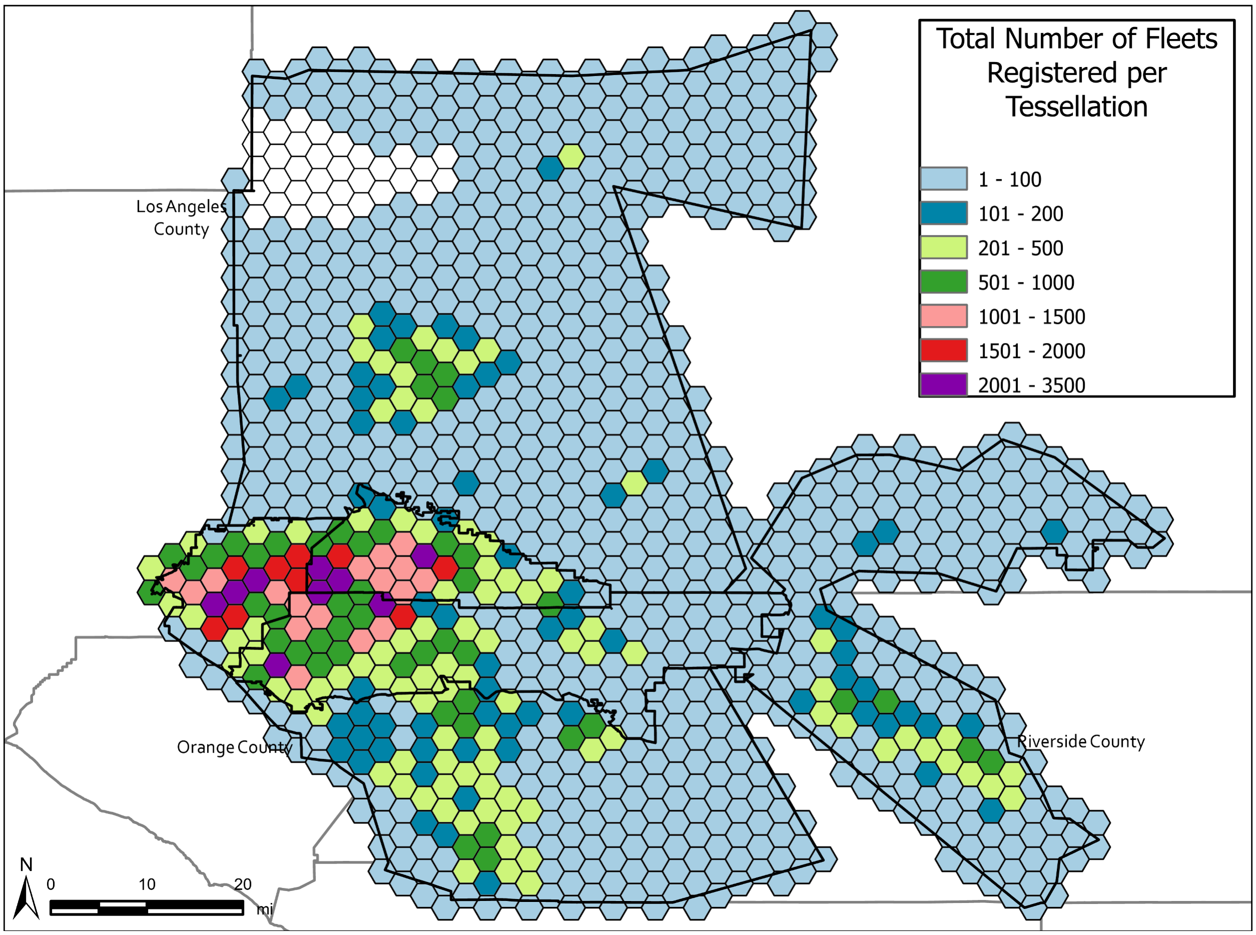
Figure 12 represents an index reflecting independent owners, branch operations, and headquarter businesses in the IE. The index is based on a composite measure that integrates the count of businesses with their average facility square footage, providing insight into both the prevalence of businesses and their operational scale. In all three maps, hexagonal areas are color-coded to represent the number of businesses within that space. The color scale ranges from blue for the lowest number of businesses (0–50) to red for the highest (1,001–2,200).

Map 1 shows a relatively high concentration of independent owners, within the E, NC, and SC subregions. We also noticed a high density of independent businesses in the N, E, and S, with lower index with respect to the other subregions. Map 2 depicts branch operations following the same trend of the independent owners. On the other hand, Map 3, which represents businesses' headquarters, shows the least density with very few businesses in the IE.

4.5 Registered MDHDVs in the Inland Empire

This section delves into the current fuel distribution of MDHDVs across the IE. With a focus on diesel, gasoline, natural gas, and electric fleets, we explore the scope for electrification. The mapping of these fuel types offers insights into targeted areas for intervention and the future trajectory for electrifying MDHDVs.

Figure 13. Total Fleet Registrations per Grid Tessellation, 2021



Source: California Air Resources Board, 2021

The map in Figure 13 depicts the distribution of MDHDVs across the IE region. The color coding on the map represents the number of MDHDVs registered per tessellation, with light blue indicating the lowest number, ranging from 0–100 vehicles, and purple representing the highest number, between 2,001 to 3,500 vehicles. According to the map, MDHDVs are most densely concentrated in the W, NC, and SC subregions of the IE. This is followed by lesser yet significant concentrations in the N, S, and E subregions.

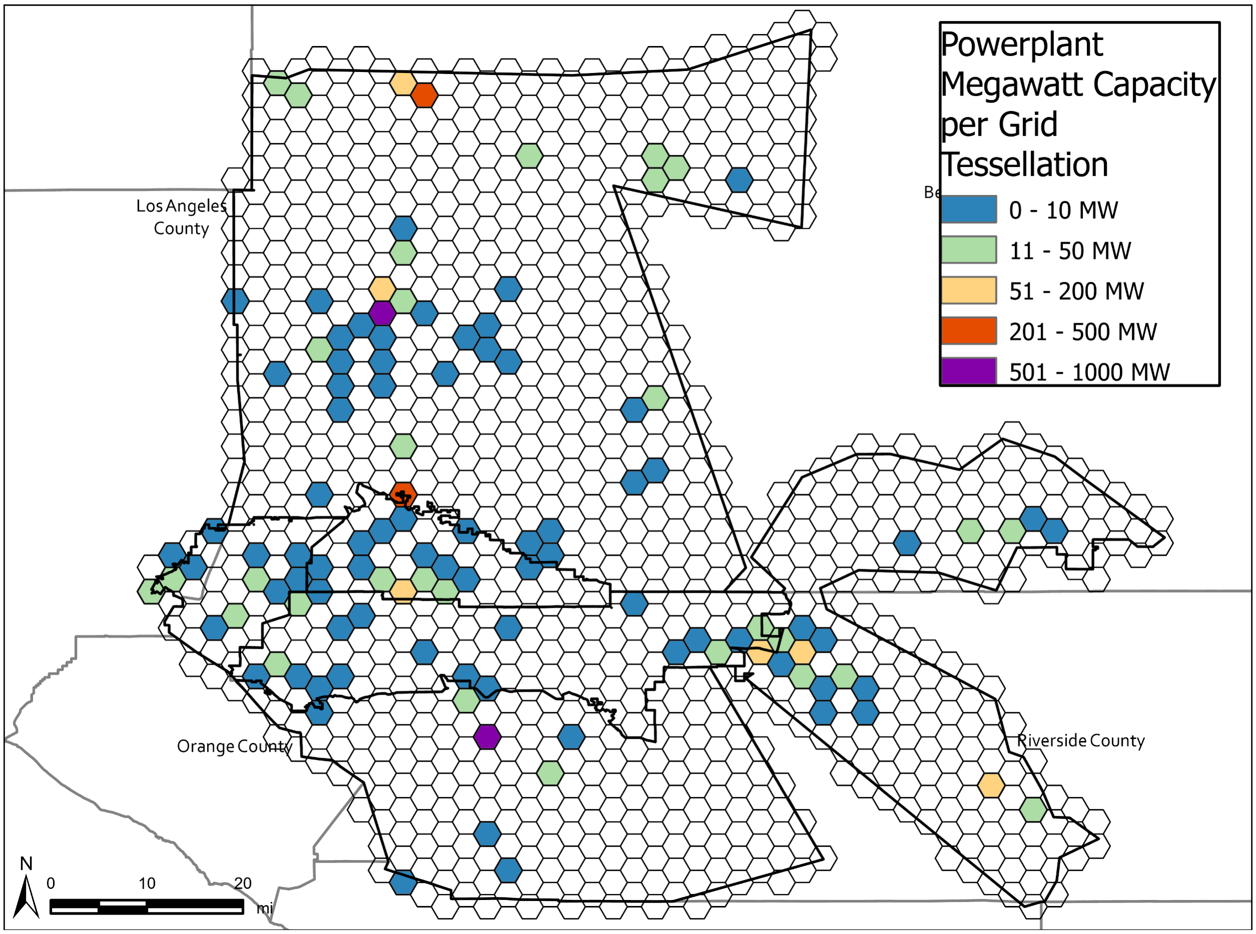
4.6 Utilities

Power Plants

The map in Figure 14 detailing the power plant capacities within the IE and its surroundings presents a crucial variable in the region's readiness for advancing the electrification of MDHDVs. The data, segmented by the megawatt (MW) capacity of each grid tessellation, demonstrates a varied landscape of energy production capabilities, ranging from 0 to 1,000 MW. In the context of green versus non-green energy sources in the IE, there are wind, solar, and plants, along with landfill gas categorized as green sources due to their renewable nature and relatively minimal environmental impact. On the other hand, the IE also has oil, biomass, gas, natural gas, and bituminous coal which are considered non-green sources, as they are primarily non-renewable and have a higher environmental impact.

In Riverside County, after 2020, solar energy has surged, becoming the second-largest source of energy generation, while natural gas and petroleum still lead, accounting for over 50% of the county's energy mix. In contrast, San Bernardino County has seen solar energy rise to represent around 25% of its energy generation, with natural gas and petroleum maintaining a dominant position. The decline in coal, biomass, and hydroelectric power, which now represent a small percentage of the total, suggests a pivot towards cleaner energy sources. This transition supports the electrification of MDHDVs, as the growing solar capacity could provide a sustainable electricity supply for EV charging infrastructures, essential for the future of transportation electrification (Center of Sustainable Energy, 2023).

Figure 14. Total Megawatt Capacity Produced by Power Plants in the Inland Empire, 2021



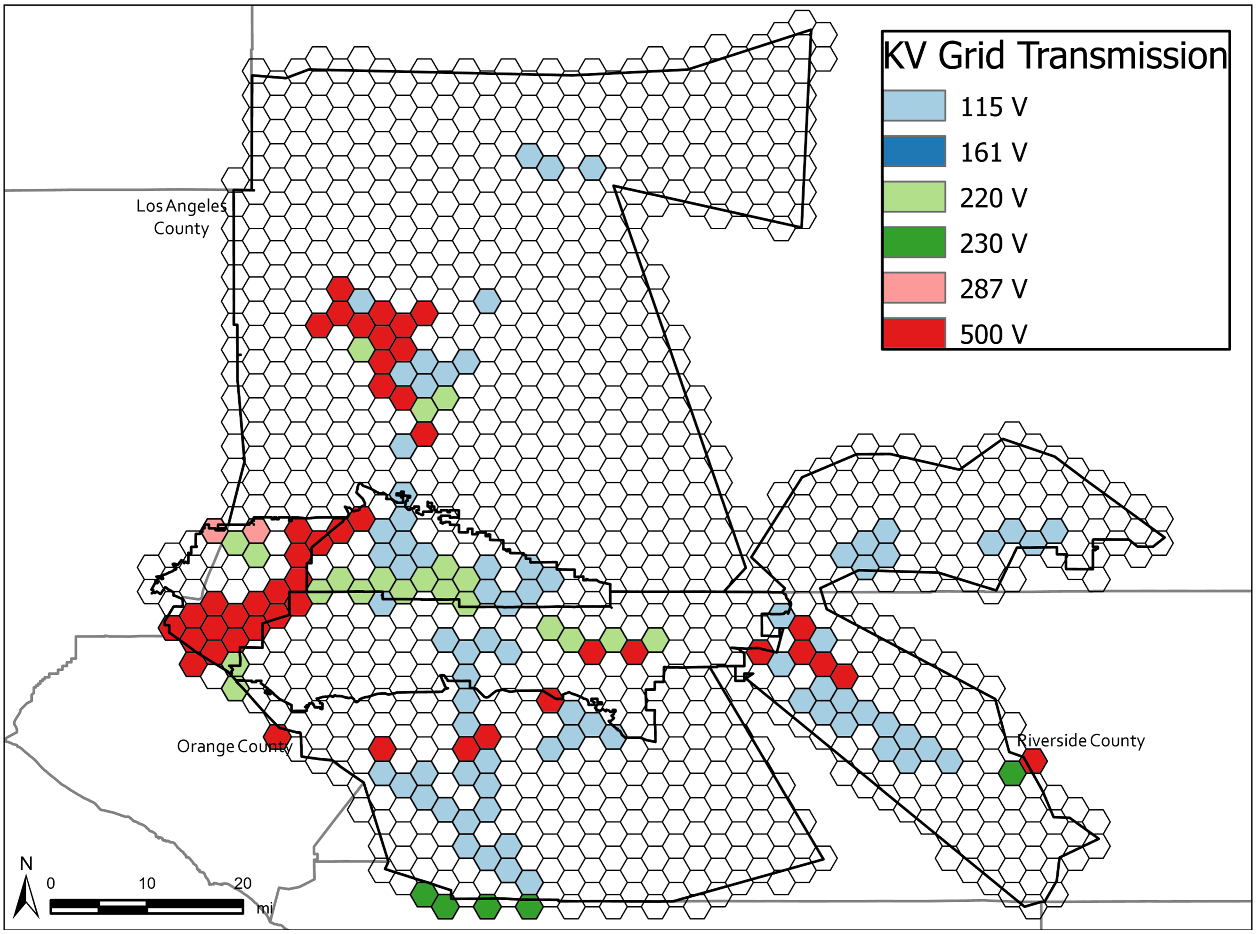
Source: California Energy Commission, 2021

Figure 14 illustrates the distribution of power plant capacities across the six subregions of the IE, categorized by their megawatt (MW) output. Each hexagon on the grid represents a geographical area, colored to indicate the total MW capacity of power plants within that area. The color scale ranges from light blue for the lowest capacity (0–10 MW) to dark red for the highest capacity (501–1,000 MW).The presence of higher-capacity power plants, particularly those in the 501–1000 MW range, indicates robust energy generation facilities. Most of these power plants are in the N subregion; another one is in the S subregion. The power plants that generate 0–200 MW are distributed in the SC, NC, W, and E subregions with higher concentration in the W and NC subregions.

Assessment of Grid Transmission Capacities in the Inland Empire

The electrical grid's transmission capacity within the IE is a crucial indicator of the region's ability to distribute electric power. The map's hexagonal tessellation conveys the varying levels of transmission voltages, which are fundamental to understanding the grid's capability to meet current demands and to support additional loads from future developments, like the expansion of EV charging infrastructure.

Figure 15. Grid Transmission Capacity (kV) Across the Inland Empire



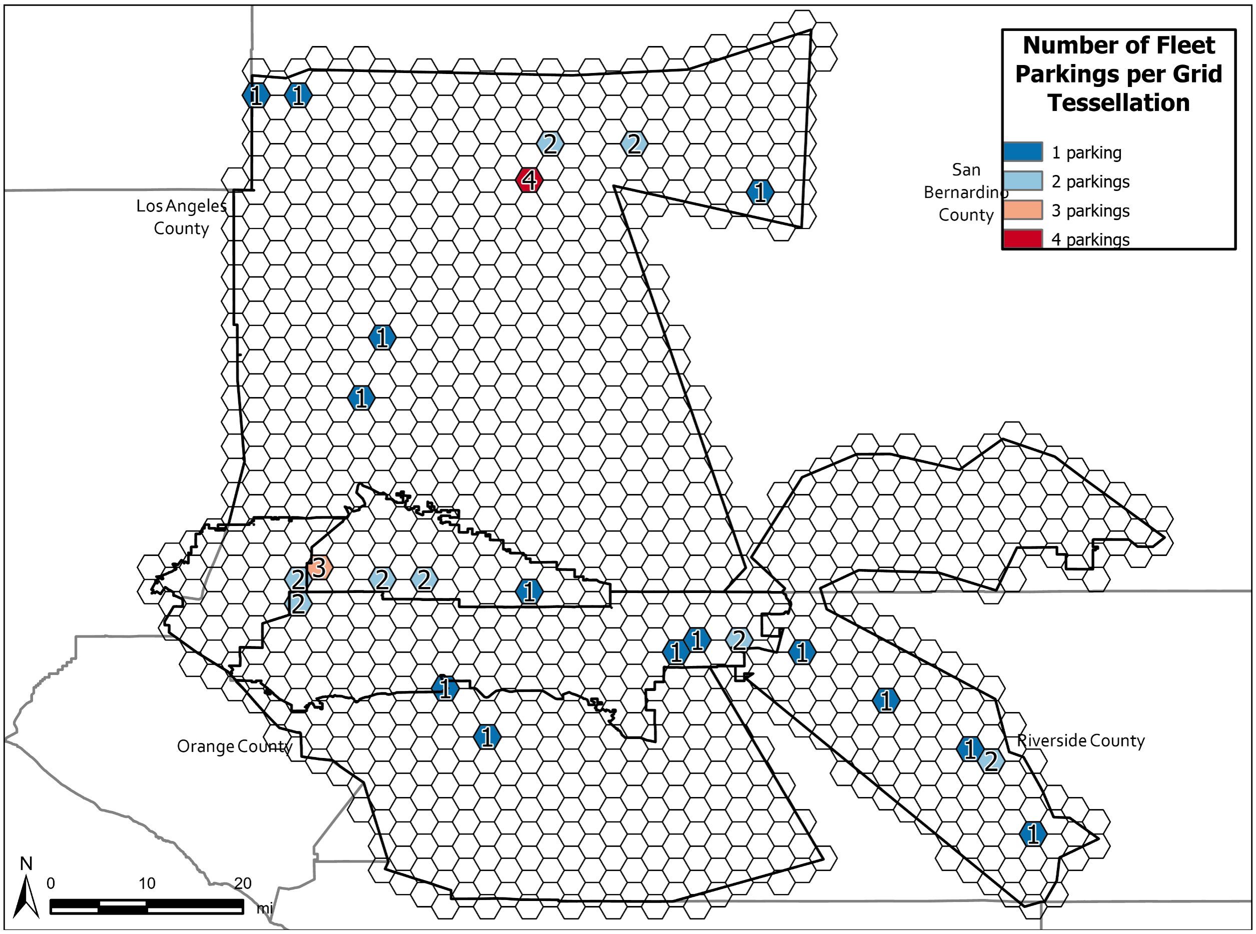
Source: California Energy Commission, 2021

Figure 15 is a hexagon grid map that shows the grid transmission capacity in different subregions, categorized by voltage levels. The color-coded legend ranges from light blue for the lowest voltage level (115 V), to dark red for the highest voltage level (500 V). The dark red hexagons, indicating the 500 V transmission capacity, are predominantly located in the N and W subregions. There are also some isolated high-capacity transmission hexagons in the E and southern S subregions, but these are not shown as connected clusters. The NC and SC subregions are represented by hexagons with colors representing the lower end of the voltage spectrum, suggesting lower transmission capacities in these areas.

4.7 MDHDVs Parking Analysis in the Inland Empire

As a region with diverse transportation needs, the IE offers several fleet parking options. The 2022 Caltrans parking study provides insight into these options, detailing the parking availability for fleets across the region. Figure 16 illustrates the findings from this study, highlighting the distribution and density of fleet parking spaces throughout the IE (Caltrans, 2022).

Figure 16. Hexagonal Grid Tessellation Visualization of Fleet Parking Availability in the Inland Empire Region, 2021



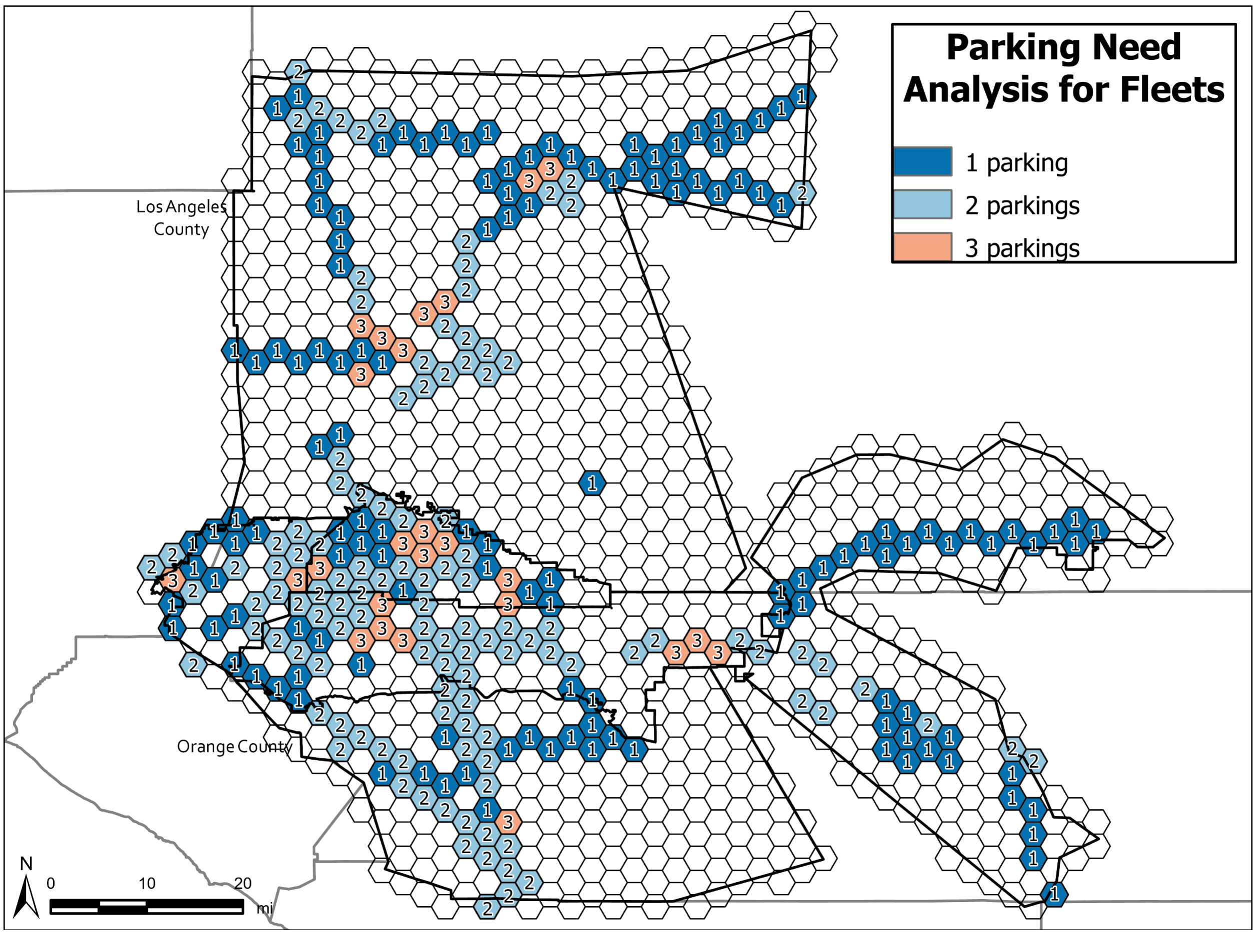
Source: California Department of Transportation, 2021

Figure 16 uses a hexagonal grid to represent the availability of fleet parking in a given geographic area. Color coding on the map indicates the number of fleet parking or truck dwelling/resting areas within each grid cell: blue for one parking, light blue for two parkings, orange for three parkings, and red for four parkings.

Upon examination of the map, it is evident that fleet parking is quite dispersed. There is only one hexagonal grid cell indicating the presence of four fleet parking, colored red, located in the N subregion. Similarly, a single cell colored orange, signifying three fleet parking, is found in the NC subregion. The cells colored light blue, which represents two fleet parkings, are seen solely in the E and S subregions. The rest of the map, covering all six subregions, is predominantly marked with intermittent blue cells, each indicating the presence of a single fleet parking.

After the visualization of existing fleet parking, Figure 17 shows the parking demand analysis for fleet vehicles within the IE. It employs a hexagonal grid to depict the estimated demand for fleet parking across different sectors of the region (Caltrans, 2022).

Figure 17. Hexagonal Grid Tessellation Visualization of Fleet Parking Demand Analysis in the Inland Empire Region, 2021



Source: California Department of Transportation, 2021

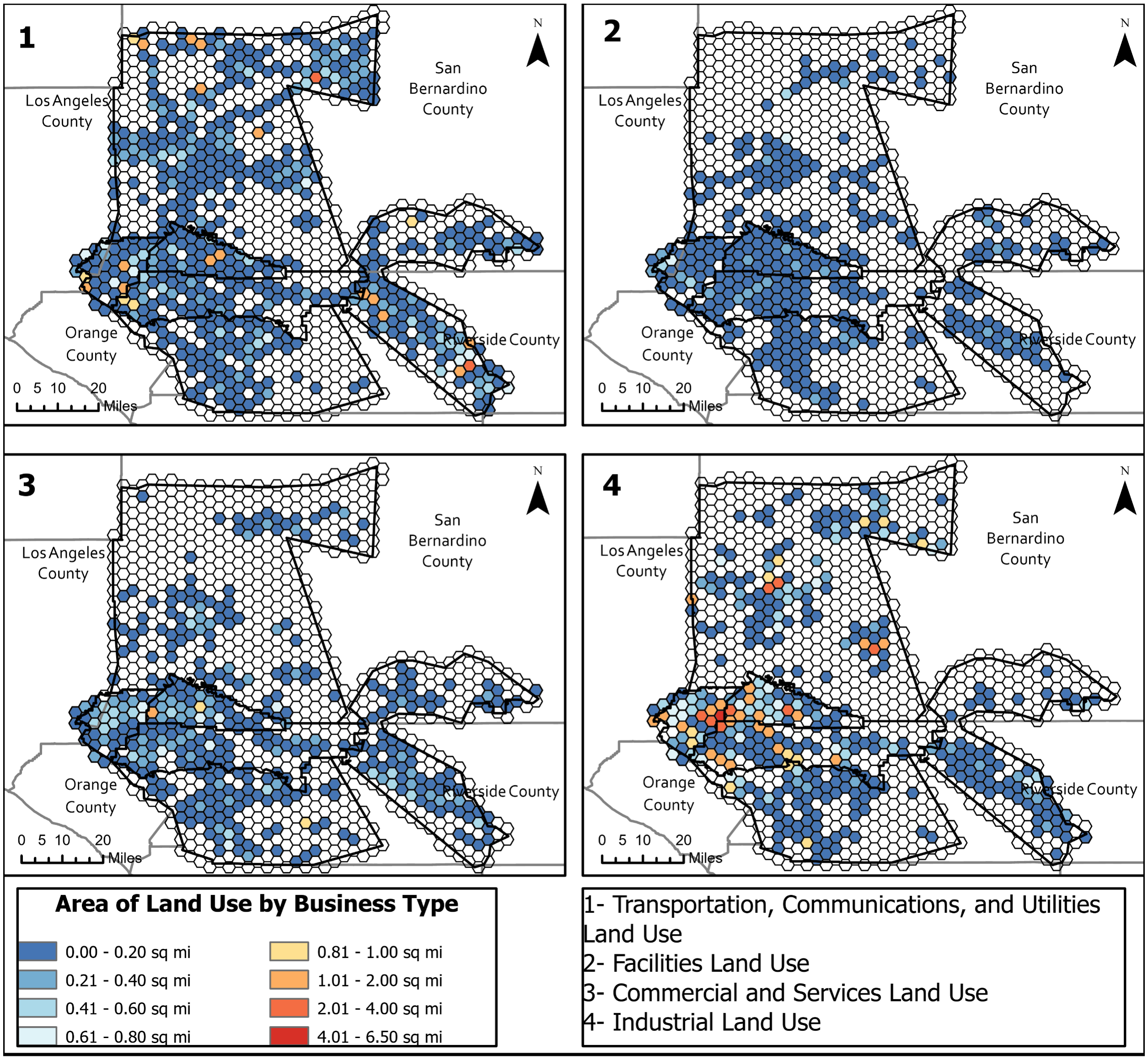
In Figure 17, the map provides an overview of parking demand for fleets, using a color-coded legend to indicate the number of required parking spots within each hexagonal grid cell. The colors represent different levels of parking demand: blue for one parking, light blue for two parkings, and orange for three parkings.

There is a substantial demand for MDHDV parking across the W, NC, and SC subregions, with most grid cells indicating a requirement for one to three parking spots. The NC subregion exhibits the greatest demand for fleet parking, with numerous cells colored orange, which corresponds to the highest parking demand of three spots per cell. This reality is also evident in the SC subregion, where there is a similar demand for parking. The N subregion displays a notable parking demand as well, with eight hexagonal grid cells requiring three parkings each. On the other hand, the S subregion shows the least demand for parking, followed by the E subregion.

4.8 Land Use

This section presents a series of four maps offering a visual representation of land use distribution within a specified region, categorized by business types according to the North American Industry Classification System (NAICS). Each map is also methodically divided into six subregions—N, S, E, W, NC, and SC—to facilitate a detailed regional analysis.

Figure 18. Distribution of Business-Centric Land Use in the Inland Empire by Type and Total

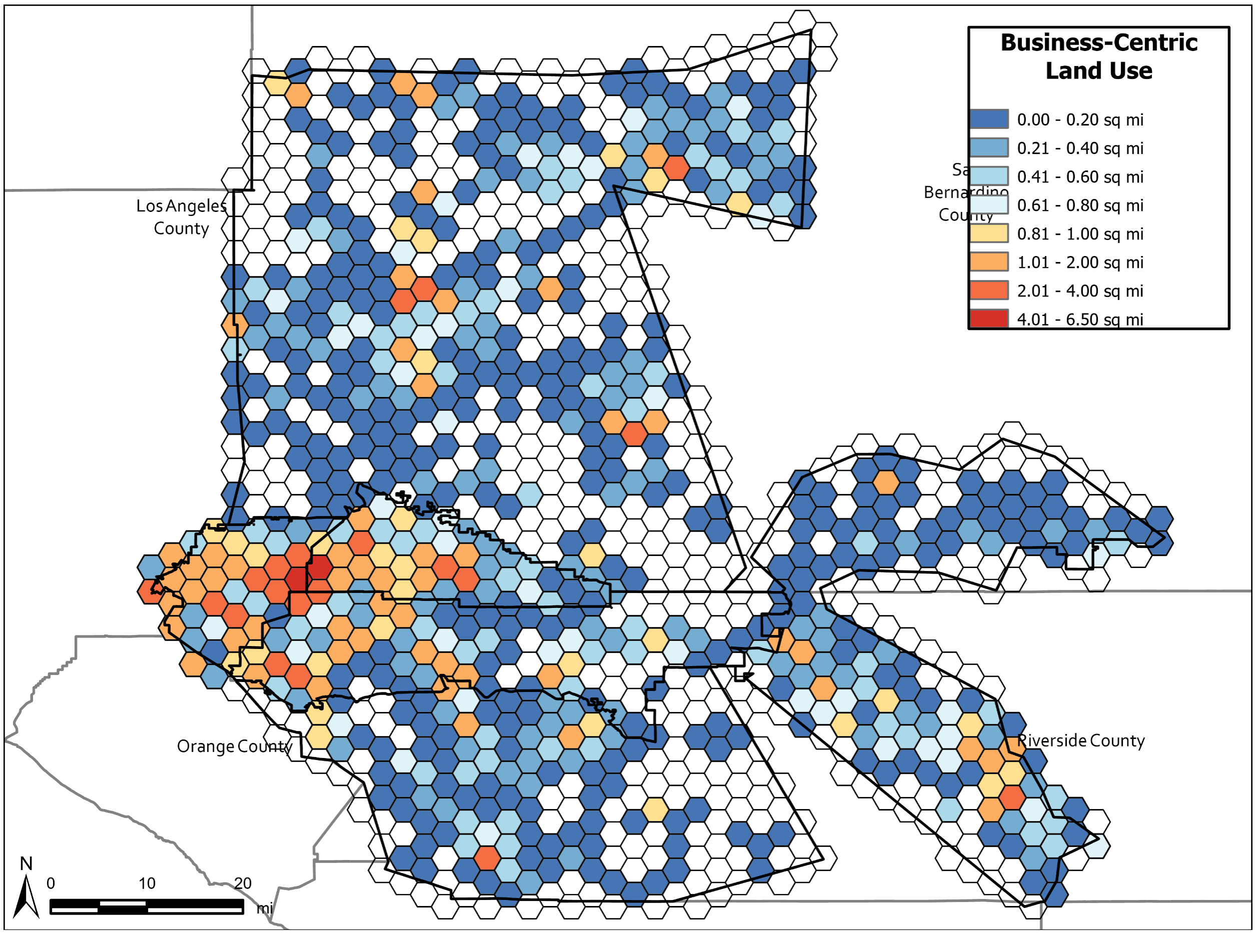


Source: Southern California Association of Governments, 2021

In Figure 18, the color legend at the bottom of the figure indicates the area of land use in square miles, with a scale ranging from dark blue for the smallest area (0.00–0.20 sq mi) to dark red for the largest area (4.01–6.50 sq mi). Map 1 represents "Transportation, Communications, and Utilities Land Use." The distribution of this land use is dispersed across the subregions, with no significant concentration in any area. Map 2 is the "Facilities Land Use," where notably the W, NC, and SC subregions have a denser concentration of facilities land use than the other subregions. Map 3 shows "Commercial and Services Land Use" with the same description; however, with even more concentration in the NC subregion. Map 4 illustrates "Industrial Land Use." It shows that industrial land use is the most dominant, particularly in the W, NC, and SC subregions, indicated by the presence of darker blue shades which represent larger areas of land use.

Figure 19 shows the total of these businesses per land use area. This figure helps us understand where most businesses are located per subregion.

Figure 19. Distribution of Business-Centric Land Use in the Inland Empire by Type and Total



Source: Southern California Association of Governments, 2021

Figure 19 offers a detailed visual analysis of business-centric land use across the IE, categorizing different areas by the extent of business occupation within the six designated subregions: N, S, E, W, NC, and SC. The color-coded legend is the same as the previous figure.

The darkest shades of red and orange represent areas where the land use for business purposes is most extensive, highlighting a higher concentration of businesses. These predominant areas fall within the W, NC, and SC subregions, as evidenced by the clusters of darkly colored hexagons. This visualization points to a significant accumulation of business activities in these parts of the map. Other regions, such as N, S, and E, exhibit a more mixed distribution of land use intensities with varying shades of blue and fewer instances of the darker reds and oranges, suggesting a less dense aggregation of business-centric land use. This arrangement allows for an immediate grasp of the spatial patterns of business distribution and land occupancy without delving into the underlying causes or implications of these patterns.

4.9 Summary Points

The comprehensive analysis encompassing traffic OD, fleet dwell counts, and land use within the IE provides valuable insights into the region's transportation dynamics and infrastructure. The study, utilizing Streetlight Data, reveals significant variations in bidirectional trips across the IE's subregions, highlighting key areas with high traffic density and diverse travel patterns for different vehicle classes. Particularly notable is the concentration of trips in the W, NC, and SC subregions, with varying densities in other areas. High dwell counts in specific subregions suggest concentrated areas of vehicle activity, informing where charging infrastructure and other transportation facilities may be most needed. The average dwell times further highlight the operational dynamics of these vehicles with shorter dwell times versus longer stops.

The section also explores the relationship between business land use and transportation facilities in the IE. By developing an index that merges business count with facility square footage, the analysis offers a comprehensive view of the business landscape, correlating the density and operational scale of business entities with regional truck traffic movement.

Furthermore, the assessment of registered MDHDVs in the IE, including their fuel distribution, indicates potential areas for electrification intervention and the future trajectory for electrifying these vehicles.

Lastly, the analysis of power plant capacities and grid transmission capabilities in the IE underscores the region's first step towards identifying the readiness for advancing the electrification of MDHDVs. Identifying areas with robust energy generation facilities and assessing the electrical grid's capacity to distribute power are key factors in supporting the transition to electric vehicles.

5. Analysis and Discussion

5.1 Introduction

As we delve into the comprehensive analysis of electrification strategies for MDHDVs across the diverse subregions of the IE, it becomes evident that a one-size-fits-all approach is insufficient. The forthcoming subsections will offer an in-depth analysis of each subregion—West (W), North-Center (NC), South-Center (SC), North (N), South (S), and East (E)—based on the figures provided in Section 4. The following analysis highlights the unique transportation dynamics, economic frameworks, and infrastructure requirements of each subregion to support electrification pathways. This analysis aims to outline these regional variances and highlights the specific needs and capacities of each subregion. By doing so, a regional overview is provided that is both practical and sustainable, ensuring that the transition to electric MDHDVs aligns with broader California sustainability goals.

5.2 The West Subregion

We start with the West, one of the most active IE subregions. It has a complex interplay between transportation logistics, economic vitality, and the emergent challenges and opportunities posed by the electrification of MDHDVs. A granular examination of the bidirectional OD traffic patterns reveals a pronounced dichotomy between MDVs and HDVs, each with distinct operational profiles. Most of the trips were on the upper scale with respect to the other subregions, except the bidirectional trips of MDVs coming or going to the W and the outside buffer area—meaning that most of the trips were happening within the subregion or between the subregion and the buffer zone.

For HDVs characterized by high dwell counts and average dwell time, depot charging appears to be a viable solution. The protracted dwell times suggest that these vehicles, primarily engaged in long-haul operations, could benefit from overnight charging solutions. This would allow for a full recharge in alignment with drivers' mandated rest periods. However, the data also shows a very low number of fleet parking options and a high need for parking, making overnight charging a challenge for drivers. In contrast, MDVs, despite their medium to high average dwell time, may be engaged in more dynamic regional delivery services that allow for intermittent opportunity charging. This could occur at various nodes within the W subregion's extensive transportation and warehousing network, where vehicles have shorter, albeit frequent, idle periods that could be utilized for incremental battery top-ups.

Furthermore, the existing high grid transmission capacity in the W subregion is conducive to the proliferation of MDHD EV charging stations. However, the "low" power plant capacity signals potential constraints in the local generation of electricity, which could stymie the transition unless addressed by supplementing generation capacity or by importing power from outside the subregion.

The high number of business-centric land use and the high number of registered MDHDVs geared towards transportation and warehousing functions within the W subregion suggests that these businesses must be considered a primary stakeholder in the EV transition. This is reinforced by the significant presence of independent owners and branch operations. The shift to electrification must, therefore, consider the economic implications for these stakeholders, particularly in the design of charging infrastructure that accommodates the varied patterns of MDHDVs, ensuring minimal disruption to operational logistics and supply chain continuity, especially for the independent owners.

The interrelation between vehicular activity, economic considerations, and charging infrastructure requirements underscores the complexity of advancing MDHDV electrification. Electrification strategies must be tailored to the operational patterns of MDHDVs, accounting for the varying dwell times and the subregion's infrastructure capacities. This entails a systemic integration of charging infrastructure within existing transportation and warehousing hubs, aligned with the region's grid capabilities, and cognizant of the potential socioeconomic impacts on the dominant independent business structure.

5.3 The North-Center Subregion

Like the West subregion, the North-Center subregion of the IE is also an active and vibrant subregion. In the NC subregion, HDVs exhibit very high OD traffic within the NC and the buffer zone, coupled with significant dwell counts. This high level of HDV activity aligns with the subregion's status as a freight corridor with an abundance of warehousing and distribution centers. The substantial dwell times of these vehicles underscore the feasibility of depot charging strategies, where HDVs can be charged during regulated rest periods or scheduled downtimes. This approach would necessitate a strategic placement of charging stations at logistic hubs and warehouses that are prevalent within the NC subregion, since truck parking is low with respect to the demand.

Conversely, MDVs, while also active, present a diversified pattern of shorter, albeit high volume, dwell times, which may correspond to a more dynamic operational rhythm with frequent stops—ideal for opportunity charging. The opportunity charging infrastructure would need to be strategically dispersed across the subregion's nodes of economic activity, enabling MDVs to recharge during operational breaks without deterring their tight delivery schedules. In addition, having charging options at the transportation and warehousing facilities is a very important factor that will help the transition.

The existing grid transmission capacity in the NC subregion is moderate, presenting a challenge to the widespread adoption of MDHD EVs. An augmentation of this capacity is essential to support the additional load imposed by MDHD EV charging demands. This necessity becomes even more pronounced when considering the high need for fleet parking, indicating a substantial volume of MDHDVs that could transition to electric fleets and therefore require reliable charging options.

The complex and high distribution of business-centric land use in the NC subregion, particularly within transportation, warehousing, and utilities, emphasizes the importance of these sectors to the local economy. The electrification of MDHDVs must, therefore, be integrated into the broader economic framework, ensuring that the transition supports and sustains the subregion's critical economic sectors. The focus on electrification must align with the operational logistics inherent to the region's industrial fabric, which is heavily reliant on MDHDVs for the movement and distribution of goods.

Considering the subregion's business ownership structures, the transition to electrification requires careful planning to support the predominantly high number of independent owners and branch operations. As these stakeholders are integral to the subregion's economic landscape, their engagement and inclusion in planning EV infrastructure and opportunity charging is very crucial. This approach will mitigate potential disruptions and foster a collaborative transition towards sustainable transport solutions.

5.4 The South-Center Subregion

Like the East and the North-Center subregions, the South-Center subregion presents its own unique challenges and opportunities for the electrification of MDHDVs, particularly when examining the interrelated aspects of vehicle traffic patterns, dwell times, economic structures, and the potential for charging infrastructure.

In terms of bidirectional OD traffic patterns, the SC subregion demonstrates high activity for both MDVs and HDVs. However, the HDV traffic is not as excessive as in other subregions, suggesting a more balanced distribution of vehicle types and potentially more diverse transportation needs. The high dwell count for MDVs implies a significant stationary presence, which could be attributed to regional delivery and service operations that tend to have fixed and predictable stops, making them suitable for several charging solutions.

The presence of relatively lower average dwell times for HDVs in the SC subregion suggests these vehicles, while not as stationary as those in other subregions, still present significant opportunities for the integration of depot charging stations. These could be strategically located at distribution centers and truck stops where vehicles are known to take mandatory rest breaks. The infrastructure for such charging stations would need to be robust enough to handle the significant power requirements of HDVs with the low number of truck parking available.

For MDVs, the high dwell count and the moderate average dwell time underscore the need for a network of opportunity charging stations. These would cater to the operational patterns of MDVs, enabling them to charge during shorter stops throughout their delivery routes or while staging. Such a network would enhance the operational efficiency of MDVs, ensuring they can maintain their service levels while transitioning to electric.

The SC subregion's electricity generation and grid transmission capacity is low, making it a burden for the infrastructure to support the transition. Furthermore, the economic fabric of the SC subregion, characterized by a blend of a high number of independent owners, must be a key consideration in the electrification strategy. The transition to electric MDHDVs should not only be technologically feasible but also economically viable for these businesses. Any electrification plan would need to include financial models or incentives that enable these smaller entities to invest in EVs and the associated charging infrastructure.

5.5 The North Subregion

The analysis of bidirectional OD traffic patterns reveals a comparatively lower activity level for MDVs within the North subregion, suggesting that logistical flows are less intense than in other subregions. However, HDV traffic is noted to be moderate to high in some areas, indicating that while the volume is lower, there is a significant presence of long-haul operations which are characteristic of HDVs.

This traffic for HDVs coupled with low dwell counts for MDVs suggests that depot charging infrastructure might be more appropriate for HDVs in this subregion, given that these vehicles are likely engaged in operations that allow for longer charging periods, possibly in line with regulated rest periods. From an economic standpoint, the N subregion's reliance on HDV traffic for goods movement implies that any strategy for MDHDV electrification must consider the operational patterns of these vehicles. The impact of electrification on the long-haul trucking industry, which may require more substantial infrastructure investments such as depot charging, could be significant. The need for this type of infrastructure is also underscored by the Barstow area, which is a noted node for HDV traffic, suggesting a potential hub for depot charging facilities.

The grid transmission capacity in the N subregion is moderate, which indicates that while there may be some capability to support additional electrical load from MDHD EV charging, significant upgrades may be necessary to accommodate a large-scale rollout of MDHDV electrification. Given that the power plant capacity in the N subregion is described as high, there is potential to leverage this capacity to support an expanded grid infrastructure for EV charging.

Regarding the parking need analysis, the moderate need for fleet parking suggests that while there is some demand for MDHDV parking infrastructure, it may not be as critical as in other subregions. This could indicate that there are some facilities to support current MDHDV operations, which may also be used for depot charging sites.

In terms of business-centric land use, the N subregion exhibits medium levels, suggesting that while there is significant economic activity, it is not as concentrated in the transportation and warehousing sectors as in other subregions. This could imply that the electrification strategy in the N subregion could focus more on supporting HDVs associated with long-haul freight operations rather than a broad spectrum of commercial activities.

5.6 The South Subregion

Moving to the analysis of the South subregion, the bidirectional OD traffic patterns reflect an intermediate level of activity for MDVs and a low level for HDVs. This indicates a lower intensity of logistical operations in comparison to other subregions, with implications for the type and scale of required electric vehicle (EV) charging infrastructure.

Given the medium dwell count for MDVs, it can be inferred that there are vehicles in regional delivery operations which could necessitate a moderate deployment of opportunity charging strategies. These would enable MDVs to charge during their operational day without significant deviation from their delivery routes, enhancing their efficiency while transitioning to electric power. The low dwell time and count for HDVs, on the other hand, suggest that long-haul operations are not as dominant in the S subregion. This reduces the immediate need for extensive depot charging infrastructure typically associated with HDVs.

The electrification approach must also consider the moderate power plant and high grid transmission capacities present in the S subregion. The robust grid transmission infrastructure is an asset that can support opportunity charging, catering to electrification needs without overwhelming the existing grid. This is complemented by moderate power plant capacity, which suggests room for growth in electricity generation to meet the increasing demand as the MDHDV fleet transitions to electric.

In terms of the economic landscape, the S subregion shows a lower emphasis on transportation and warehousing activities compared to other areas, with business-centric land use being moderate. This could imply that the transition to electrified MDHDVs might not have as pronounced an impact on the local economy as it would in regions more heavily reliant on these sectors. Nevertheless, the transition must still be managed carefully to ensure that it supports sustainable economic growth and does not disadvantage the existing MDHDV-related businesses.

Moreover, the S subregion's moderate need for fleet parking highlights a potential area for dual-use infrastructure development where parking areas can be equipped with charging stations, thus serving as multipurpose facilities that contribute to operational efficiency and the promotion of EV adoption among MDHDVs.

5.7 The East Subregion

The final subregion, the East, presents a particular set of circumstances that influence the strategic planning for the electrification of MDHDVs. An examination of bidirectional OD traffic patterns reveals moderate levels of activity for both MDVs and HDVs within the E subregion. This suggests a more balanced mix of regional-short-haul and long-haul vehicle operations, necessitating a flexible approach to electrification infrastructure that caters to varied usage patterns.

For MDVs, the moderate dwell times indicate that opportunity charging stations should be integrated at key locations such as distribution centers, industrial parks, and along major transport routes. These stations would enable vehicles to charge during scheduled breaks, loading, and unloading operations, typically occurring throughout the day as part of their regular operational cycles.

The electrification efforts in the E subregion must also consider the existing electrical infrastructure. With medium power plant capacity and high grid transmission capacity, there is an opportunity to leverage the robust grid for the development of charging infrastructure. However, the moderate generation capacity may require careful planning to ensure adequate power supply for a growing fleet of electrified MDHDVs, potentially necessitating investment in additional renewable energy sources or energy storage solutions.

Economically, the E subregion's moderate business-centric land use suggests a diverse industrial and commercial base, which could benefit from the transition to MDHDV electrification through reduced operational costs and improved air quality. The move towards electrification must be aligned with the business models and operational logistics of the region's industries to ensure that it supports economic growth and enhances the competitiveness of local businesses.

In terms of parking need analysis, the E subregion's moderate need for fleet parking reflects a demand for parking infrastructure that could be developed into multi-functional spaces, combining parking with EV charging facilities. This approach would not only address current parking needs but also prepare the subregion for future increases in MDHDV traffic as the economy grows.

5.8 The Inland Empire

The W and NC subregions, both showcasing high HDV traffic with significant dwell times, necessitate a shared focus on depot charging solutions. However, contrasting them with the SC and S subregions, where MDV activity is more pronounced, suggests the need for a regional strategy blending depot charging with opportunity charging strategies. This integration caters to the dynamic operational rhythms across subregions, from long-haul HDV operations in the N to varied MDV patterns in the SC.

The divergent grid capacities—high in the W but moderate in the NC and SC—call for a unified approach to enhancing grid infrastructure. This could involve leveraging the high grid transmission capacity in the W to support adjacent subregions, coupled with bolstering local generation capacities where needed. Economically, the transition must be sensitive to the dominant business structures, from the transportation-heavy W and NC to the more diversified S and E. This necessitates a collaborative framework, ensuring that electrification aligns with and supports the economic fabric of each subregion.

The varied traffic patterns across subregions, from the balanced vehicle types in the SC to the high MDV dwell count in the S, demand an interconnected fleet management strategy. This involves coordinating electrification efforts such that the charging infrastructure in one subregion complements the operational needs of another. For instance, depot charging hubs in the W and N could serve as key nodes for long-haul HDVs, while opportunity charging points in the SC and E cater to regional MDV operations.

The transition impacts a range of stakeholders, from independent owners in the W and NC to larger corporations in the S and E. A region-wide electrification plan must engage these diverse groups, understanding their unique needs and operational patterns. This could involve creating incentive programs for smaller businesses in the SC and S, while coordinating with larger entities in the W and NC for infrastructure development.

Lastly, the transition to electrification must be cognizant of the environmental impact across subregions. This includes considering the emission reductions in heavily trafficked areas like the W and NC, and the potential for improved air quality in the S and E. Socioeconomically, the plan should aim to boost local economies, create jobs, and ensure a just transition for all workers and residents affected by the shift in vehicular technology.

The IE's transition to MDHDV electrification requires a nuanced, interconnected approach that harmonizes the distinct needs and capacities of each subregion. This involves a strategic blend of charging infrastructures, grid capacity enhancements, regional fleet dynamics management, inclusive stakeholder engagement, and mindful environmental and socioeconomic planning.

5.9 Conclusion

Through analysis of the IE's subregions it is evident that the transition to electrified MDHDVs necessitates a nuanced, region-specific approach. The distinct dynamics of the subregions underscore the complexity of this transition, which must be attuned to the variegated patterns of vehicular traffic, the intricacies of economic structures, and the capacities of existing infrastructural frameworks.

This analysis crystallizes the imperative for a strategic alignment of electrification initiatives with regional infrastructural and economic realities. It necessitates a paradigm that not only accommodates the unique characteristics of each subregion but also aligns with broader environmental objectives and economic resilience. The electrification of the MDHDV fleet in the IE, while a complex endeavor, presents a pivotal opportunity to redefine the region's transportation system, bolstering its contribution to sustainable development and environmental stewardship.

Part IV: Social Equity and Business Considerations

6. Equity Considerations

6.1 Introduction

The transition to MDHD EVs presents several implications for disadvantaged communities. The anticipated reduction in environmental pollution could lead to improved health outcomes in these areas, which are often disproportionately affected by vehicular emissions (Ramirez-Ibarra & Saphores, 2023). However, this transition poses challenges for small and medium businesses within these communities, particularly concerning their adaptability and financial resilience (Nadel, 2019). The uncertainty about how these businesses will manage the shift to an electric-focused transportation sector raises concerns about their sustainability (Fleming et al., 2021). This situation necessitates the development of strategic plans and support mechanisms to balance environmental improvements with economic sustainability. It is essential to consider the potential for this transition to inadvertently widen existing disparities and to ensure that independent businesses have equitable access to the benefits of this change.

6.2 Equitable Response During a Major Economic Transition

Addressing the challenge of ensuring an equitable response during major economic transitions necessitates a multifaceted and holistic approach. Central to this is the adoption of inclusive policy-making processes, which consider the impacts of economic changes on all societal segments, particularly the vulnerable, and incorporate diverse stakeholder perspectives in decision making (Hughes & Dundon, 2023). Furthermore, the role of education and retraining programs is highlighted as critical in enabling workforce adaptability to new economic paradigms, especially in scenarios like automation or the transition to renewable energy sectors (Li, 2022).

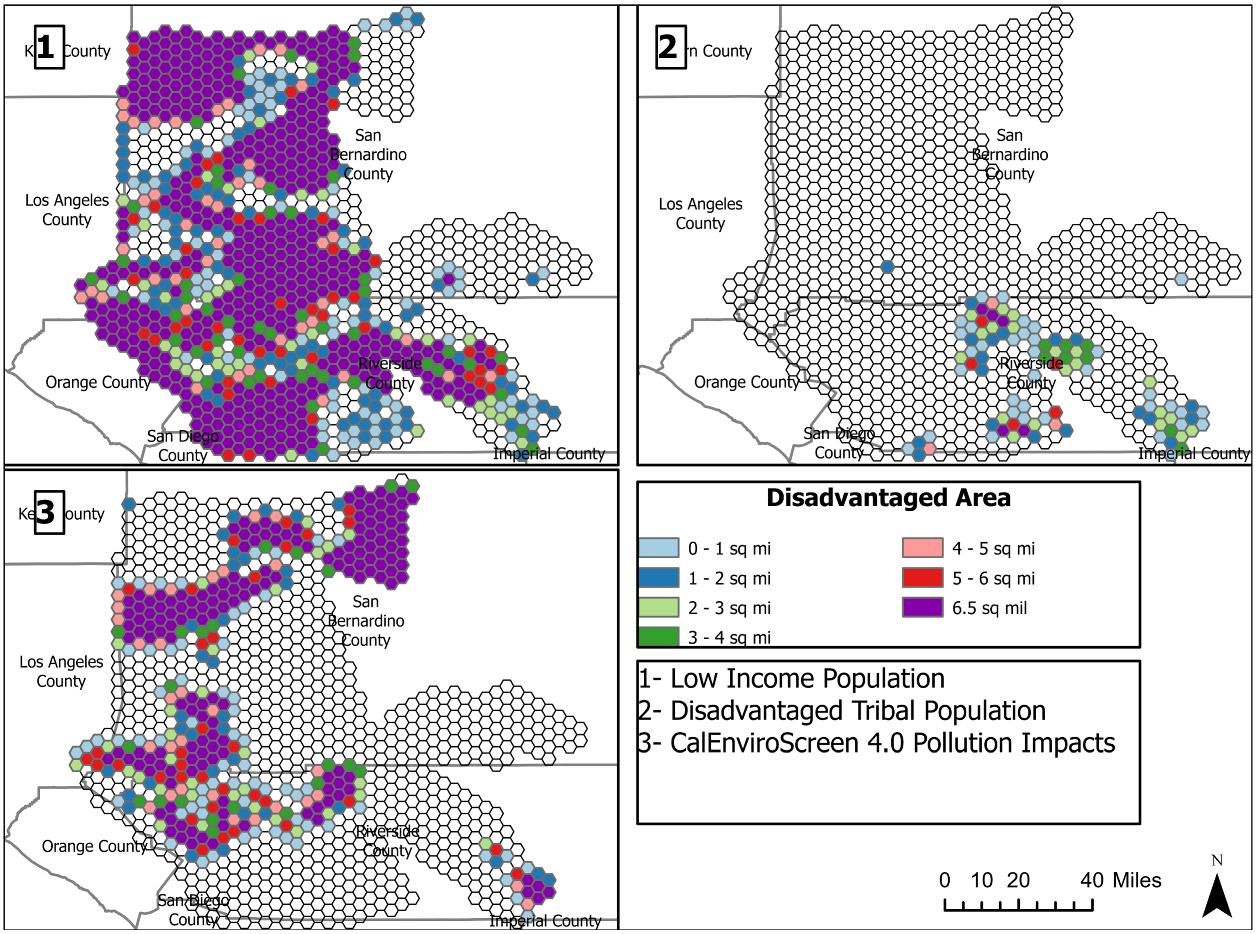
Equitable economic transitions also involve the implementation of fair taxation and redistribution measures to mitigate widening income and wealth disparities (Villani & Viscolo, 2020). Sustainable development, balancing economic growth with environmental and social equity, is a vital consideration to ensure long-term, inclusive economic prosperity (Mentes, 2023). The importance of ongoing monitoring and evaluation of economic policies is emphasized for their adjustment and effectiveness in achieving equitable outcomes (Blessett et al., 2019).

Collaborations between the public and private sectors are identified as instrumental in orchestrating more coordinated and resource-efficient responses to economic transitions (Vosman et al., 2023). Moreover, community engagement and support are fundamental in aligning economic strategies with the real-world impacts on affected populations (Puskás et al., 2021). In instances where economic transitions have global impacts, in the context of global warming and GHG emissions, international cooperation is posited as key to equitable outcomes (Quitzow et al., 2019). Lastly, the enforcement of legal protections, including fair labor practices and anti-discrimination laws, is essential in safeguarding individual rights and well-being during these transitions (Hughes & Dundon, 2023). This comprehensive approach, involving governmental, business, civil society, and international collaboration, is pivotal in ensuring that economic transitions are equitable and beneficial for all societal segments.

6.3 Understanding Disadvantaged Communities in the Inland Empire

The IE has a complex socio-economic landscape that is reflective of broader trends across the state. Here, disadvantaged communities are characterized by an intricate interplay of economic hardship, environmental challenges, and racial diversity. To understand these dynamics, it is essential to adopt a multi-faceted approach that encompasses economic indicators, tribal land considerations, and environmental factors. This analysis is further enriched by considering legislative directives and policy frameworks from the California Environmental Protection Agency (CalEPA) and the California Department of Housing and Community Development (HCD).

Figure 20. Low-Income, Tribal and Environmentally Disadvantaged Population Distribution in the Inland Empire



Source: California Air Resources Board, 2021

Figure 19 maps out the distribution of low-income populations across the IE. The different shades of color represent the density of low-income households, measured in square miles. The darkest shades indicate the highest concentration of low-income households. For example, each tessellation is 6.5 square miles, and the color purple shows the highest concentration of disadvantaged residents. This illustrates significant economic challenges in those areas. The legislative context behind this map is defined by Assembly Bill (AB) 1550, which underlines the legislative efforts to address economic disparities, making it a vital tool for identifying regions in need of economic intervention (Department of Housing and Community Development, Division of Housing Policy Development, personal communication, 2021). The second map focuses on the tribal lands within the IE, highlighting the overlap with disadvantaged community areas. Leveraging the American Indian Areas Related National Geodatabase, this map includes a provision for tribes to seek consultations with CalEPA for comprehensive representation, emphasizing the importance of integrating Indigenous perspectives in regional planning (California Environmental Protection Agency, 2023). The third map utilizes CalEnviroScreen data in alignment with Senate Bill (SB) 535 to identify disadvantaged communities based on environmental, health, and socio-economic indicators. This map is instrumental for environmental justice and health policy (California Air Resources Board, 2023; California Environmental Protection Agency, 2023).

The IE has been disproportionately affected by environmental issues, notably poor air quality due to industrial and vehicular emissions (Barth et al., 2021b). The region's heavy reliance on logistics and warehousing industries, with a substantial presence of diesel- and gasoline-fueled MDHDVs (Figure 19), has contributed to these environmental challenges. These major contributors to air pollution and greenhouse gas emissions impact marginalized communities more than others. The transition towards electrification is in progress, yet the effects on air quality and health, especially considering equitable scales, remain rarely addressed (Camilleri et al., 2023).

The conversion of MDHDVs to EVs offers numerous advantages, including the reduction of local air and traffic noise pollution (Hawkins et al., 2013; Xie, 2019). This shift is not only beneficial for the local environment but also holds potential economic benefits for the region. Electrification can lead to the creation of new jobs in green industries, offering employment opportunities to local communities. Moreover, improved air quality can lead to better health outcomes, reducing healthcare costs and enhancing the overall quality of life (Kouridis & Vlachokostas, 2022).

A significant challenge that could impede the attainment of zero-emission truck goals is the absence of a robust charging infrastructure system. Overcoming this barrier is essential, as it holds the key to unlocking substantial environmental and socio-economic benefits. Nevertheless, it is crucial to balance enthusiasm for these developments with prudence and consideration of potential downsides. For instance, developing charging stations should prioritize repurposing existing paved areas rather than converting forests or marshlands, to avoid unnecessary environmental disruption. The Opportunity Charging System (OCS) plays a pivotal role in the significance of EV infrastructure for MDHD EVs. Together, they facilitate the seamless integration of electric trucks into the transportation ecosystem (Mahesh et al., 2021)

6.4 Equitable Business Make-up

In the dynamic landscape of the IE's economy, the transportation and warehousing sector emerges as a critical component, characterized by a diverse array of business models and employment scales. Table 9 shows this diversity by delineating warehousing and transportation businesses by type and workforce size in the IE for the year 2021. It breaks down the sector into independent owners, branch operations and headquarters, providing a clear overview of the number of businesses and the breadth of their workforce, thereby offering a snapshot of the industry's structure. In Table 9, the category of independent owners is robust, with 6,077 businesses employing 42,397 individuals, indicating a significant contribution from small or individually run enterprises, where on average, each business employs roughly seven people. In contrast, the branch operations category comprises

1,745 businesses yet boasts a greater workforce personnel count of 55,607, suggesting that these larger company extensions typically maintain a higher employee count than their independent counterparts. The headquarters category, while small in business count with only 42 entities, still commands a considerable workforce of 4,317 employees. Collectively, the data in the table highlights the varied ownership structures within the IE's transportation and warehousing sector and the significant variances in workforce sizes that these different business types represent.

The transition to zero-emission vehicles without special attention paid to small and medium-sized businesses has the potential to increase childhood poverty, homelessness, and further breakdown of societal norms in regions such as the IE. The majority of businesses in this sector are independent operators with an average of 6.98 employees, as seen in Table 1. The goal, therefore, has to be to put assurances in the marketplace for the transition to be equitable.

Table 9. Warehousing and Transportation Businesses by Type, Employees, and Mean Employees per Business in the Inland Empire, 2021

Type of Business Ownership	Number of Businesses	Number of Employees	Mean Per Business
Independent Owners	6,077	42,397	6.98
Branch Operations	1,745	55,607	31.87
Head Quarters	42	4,317	102.79

Source: ESRI Business Axle, 2021

These independent small and medium-sized businesses face distinct challenges. The high initial cost of electric semi-trucks, which can range between $300,000 and $500,000, is a major barrier for smaller operators. Additionally, these businesses are currently grappling with the associated fluctuations in consumer demand (Bowman, 2023). Electric vehicles, particularly MDHD EVs, often face limitations in terms of range and payload capacities. The additional weight of electric batteries can limit the extra cargo that can be carried safely and efficiently. Also, the battery drain caused by the additional weight of MDHD EVs versus the MDHDVs can decrease the maximum range and increase range anxiety. Finally, suitable electric versions of certain types of trucks or vans may not yet be available in the market (Fletcher, 2023).

The anticipated caps on economic growth in the new EV economy are influenced by several factors. For instance, the demand for critical minerals like lithium and cobalt is expected to surge, with lithium demand projected to increase more than 40 times by 2040, according to the International Energy Agency (IEA) (IEA, 2024). Additionally, supply chain constraints are significant, as nearly 50% of the global cobalt supply comes from the Democratic Republic of the Congo, posing geopolitical risks and potential supply bottlenecks (Hong et al., 2024; CleanTechnica, 2024). The full life cycle costs of EV components reveal substantial environmental impacts. For example, the production of EV batteries can result in up to 74% more emissions than traditional internal combustion engine (ICE) vehicles during the manufacturing phase. However, over their lifetime, EVs can emit up to 50% less greenhouse gases compared to ICE vehicles, making them more environmentally beneficial in the long run (Bain & Company, 2023; CleanTechnica, 2024).

In the context of independent small and medium-sized businesses transitioning to electric trucks, workforce development and costs present significant challenges. The workforce in this scenario is primarily divided into two categories: drivers and maintenance/repair employees (Berger, 2021). Training and adapting the skillset of drivers is essential in the transition to MDHD EVs as they operate differently from traditional combustion engine vehicles. This may require drivers to adapt to new driving styles and become familiar with the nuances of electric drivetrains. For example, regenerative braking, a common feature in EVs, can significantly change the driving experience. Additionally, drivers must be trained in efficient route planning, considering the availability of charging stations and the range limitations of electric trucks. This training can involve new software and tools for route optimization. These factors are potential barriers for independent small and medium-sized businesses to sustain the transition (Nadel, 2019).

The maintenance requirements of electric trucks are considerably different from traditional diesel trucks (Nykvist & Olsson, 2021). The focus shifts from engine maintenance to battery care, electrical systems, and software diagnostics. Battery systems in electric trucks are complex and expensive. Maintenance staff need specialized training to handle these high-voltage systems safely. Understanding the life cycle of batteries, their warranty conditions, and the cost implications of replacement is crucial for efficient fleet management. Existing maintenance personnel may require xtensive training to adapt to the electric trucks' technology. This training can be a significant investment in time and resources (Barman et al., 2023). The alternative, hiring new staff already skilled in EV technology, can be costly and challenging, given the current labor market and the novelty of these skills. Electric trucks rely heavily on software for various functions, from battery management to overall vehicle performance. Maintenance staff must be proficient in using diagnostic tools and software specific to EVs. This skill set is a departure from traditional mechanical repair work and requires a different training approach. Small and medium-sized businesses must decide whether to develop in-house capabilities for maintaining electric trucks or outsource these services. In-house development means investing in training and equipment, while outsourcing can reduce immediate costs but may increase long-term operational expenses and reduce control over maintenance schedules (Nykvist & Olsson, 2021).

Despite these benefits, the battery-electric truck market is at an early stage, with fewer than 60,000 units in circulation worldwide, including approximately 20,000 units sold in 2021. Ninety percent of these were sold in China, and most were on the lighter side of the category, between 3.5 and 8 tons. However, significant growth in the market is expected in the coming years, as more governments and truck manufacturers set combustion engine truck sales phase-out targets, more models become available, and production capacity is increased (Mulero, 2023). To help independent small and medium-sized businesses succeed during this transition, they need robust support. Financial incentives and subsidies can offset the higher costs of battery-electric trucks, while affordable financing and leasing options are crucial. Investment in charging infrastructure at key locations, such as distribution centers and industrial parks, will ensure efficiency. Additionally, training and technical support for maintaining and operating new electric models will aid adaptation. Providing these resources will facilitate a more inclusive and successful transition to a zero-emission future.

6.5 Addressing Equity through Government Incentives and Rebates

Federal Incentives

The U.S. government has enacted various policies and incentives to encourage the adoption of electric trucks as part of a broader initiative to promote sustainable transportation. Key among these is the Inflation Reduction Act, which extends tax credits for EVs, including trucks, offering up to $7,500 credit until the end of 2023 and shifting to a point-of-sale credit in 2024. However, the availability of these credits is contingent on each manufacturer's sales, suggesting a selective applicability.

Additionally, the National Renewable Energy Laboratory (NREL) provides rebates for different types of EVs, including transit buses, trucks, and school buses, with the rebate amount varying depending on the vehicle type. This indicates a nuanced approach to supporting the electric vehicle sector, addressing specific needs within different vehicle categories.

Support for research and development is also a crucial aspect of federal initiatives. The Department of Energy (DOE) funds projects that focus on research, development, and demonstration of electric vehicle technologies, including trucks. This support is essential for companies and organizations involved in creating innovative solutions in the electric truck sector, indicating a clear emphasis on technological advancement and practical application.

California State Incentives

California's approach to promoting electric trucks encompasses a comprehensive range of funds and incentives, reflecting its commitment to sustainable transportation and emission reduction. Central to these efforts is the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), which offers significant vouchers, reaching up to $315,000 per vehicle, to fleets purchasing or leasing zero-emission or hybrid trucks and buses. This initiative greatly reduces the up-front costs of these vehicles. Additionally, the Clean Vehicle Rebate Project (CVRP), primarily targeting light-duty vehicles, extends its rebates to certain electric pick-up trucks that are classified as passenger vehicles, thereby expanding the range of vehicles eligible for incentives.

Beyond direct financial incentives, the California Climate Investments (CCI) program plays a vital role in funding climate initiatives, including those supporting the deployment of EVs. While not a direct incentive program, CCI's investment in related projects and programs indirectly bolsters the transition to electric trucks. Infrastructure support is also a key element, as evidenced by the EnergIIZE program, which offers incentives for the infrastructure necessary for companies and public agencies using zero-emission vehicles. This includes funding for charging infrastructure, maintenance facilities and workforce training, reflecting a holistic approach to the adoption of EVs.

The state's regulatory framework emphasizes equity in the adoption and use of zero-emission vehicles. State agencies such as the California Public Utilities Commission and the California Air Resources Board are deeply involved in setting ZEV goals, ensuring equitable access to vehicles and infrastructure, and collaborating with federal agencies to scale up and equalize opportunities for MDHD ZEVs. Manufacturers, particularly in the hydrogen fuel sector, are encouraged to focus on equitable production and distribution

Pending legislation in the California State Senate, including Senate Bill 425, is geared towards addressing equity concerns through rebate programs specifically for medium- and heavy-duty ZEVs. This proposed program includes potential incentives for fuel cell electric vehicles (FCEVs), with a focus on addressing the range challenges of larger vehicles and redefining eligibility for CVRP rebates. The legislation also aims to provide additional rebates for low-income purchasers at the point of sale and establish eligibility criteria for these rebates and state tax credits.

California Air Resources Board Incentives

The Innovative Small e-Fleet (ISEF) Pilot Program, initiated by the California Air Resources Board, is a strategic initiative aimed at mitigating the barriers small fleets and owner-operators face in adopting zero-emission trucks. It addresses critical issues such as high upfront costs, constrained financing and insurance options, and the complexities involved in establishing fueling infrastructure. By allocating a portion of the Heavy-Duty Vehicle Incentive Program (HVIP) funds specifically for small fleets, ISEF endeavors to better comprehend and meet the unique needs of this traditionally underserved demographic, facilitating their transition to zero-emission vehicles. This is particularly significant for entities subject to the Advanced Clean Fleets regulation. ISEF enables eligible small fleets to avail themselves of increased voucher amounts for a variety of innovative mechanisms, including all-inclusive leases, peer-to-peer truck sharing, truck-as-a-service, and personalized assistance with infrastructure planning.

The ISEF program's inception was bolstered by the 2021–22 Funding Plan, which earmarked it within the Clean Truck and Bus Voucher Incentive Project (HVIP) to amplify support for small fleets, pursuant to Senate Bill 372. The funding trajectory began in FY 2020–21 with an initial allocation of $25 million, which was subsequently increased by $10 million to accommodate the demand from small fleets. This upward adjustment continued into FY 2022–23, where the original $33 million allocation was augmented by an additional $50 million sourced from the broader

HVIP funds, earmarking these resources for both standard purchases and innovative solutions through ISEF. By FY 2023–24, the program was allocated $14 million, reflecting a responsive and evolving funding strategy aimed at promoting zero-emission transitions within small fleets.

This targeted approach not only enhances the environmental benefits through the reduction of emissions but also supports economic viability and sustainability for small fleet operations within California. By the end of November 2022, the program had significantly expanded its financial outreach, demonstrating CARB's commitment to advancing cleaner, more sustainable transportation solutions for small fleets. Through ISEF, CARB leverages financial incentives and innovative leasing or service models to reduce entry barriers to ZEV adoption, thereby contributing to California's broader environmental and public health goals.

South Coast Air Quality Management District (AQMD) Incentives

The South Coast Air Quality Management District's Voucher Incentive Program (VIP) is a crucial environmental initiative designed to promote the use of ZEVs in small fleet operations. By offering financial incentives to replace older, high-polluting trucks, the VIP aims to significantly reduce emissions. To qualify, fleet owners must meet operational and vehicle conditions, such as operating most of the time in California and owning vehicles from specified weight classes. The program facilitates this transition through partnerships with approved dealerships and dismantlers, ensuring a smooth process for applicants. The VIP represents a strategic investment in cleaner air and a sustainable future. For a full understanding of the program's specifics, accessing the AQMD's resources is recommended.

The SCAQMD Carl Moyer Program, as of 2023–2024, also offers financial incentives aimed at accelerating the adoption of EV charging infrastructure. Specifically targeting the reduction of emissions from HDVs, the program provides grants for the installation of battery charging stations. This initiative is critical in supporting California's environmental goals, emphasizing the

improve air quality and combat global warming and GHG emissions through innovative solutions.

Port of San Pedro Incentives

The Ports of Long Beach and Los Angeles have recently announced a significant initiative aimed at promoting the adoption of zero-emissions trucks within their operations. Together, they are making a substantial sum of $60 million accessible through HVIP. This funding is specifically allocated for the acquisition of zero-emission Class 8 drayage trucks that are essential for the efficient functioning of the San Pedro Bay ports complex.

What makes this initiative even more significant is that each of these major ports is contributing $30 million to the endeavor. This financial commitment is made possible through the Clean Truck Fund (CTF) Rate, a unique mechanism that collects $10 per twenty-foot equivalent unit from cargo owners for every loaded container entering or exiting the port complex. The CTF Rate plays a pivotal role in realizing the ambitious goals set forth by the San Pedro Bay Ports Clean Air Action Plan, which seeks to achieve 100% zero-emissions drayage trucks operating in the port complex by the year 2035.

The voucher program, a central element of this initiative, leverages the existing HVIP funding application process. HVIP, initiated by the California Air Resources Board, is an integral part of California Climate Investments, a statewide program dedicated to utilizing cap-and-trade dollars to reduce greenhouse gas emissions, bolster the economy, and enhance public health and the environment. This initiative is particularly focused on especially vulnerable communities, like those in proximity to the ports. The administration of funding is entrusted to CALSTART, the current HVIP administrator, and is allocated on a first-come, first-served basis.

What sets this program apart is the voucher enhancements provided by the ports. For fleets with 10 or fewer trucks, the voucher amount is an impressive $100,000 per truck, while fleets with more than 10 trucks receive $75,000 per truck. This initiative will help small and medium businesses and/or owner-operators to be part of the transition. These enhancements are in addition to the existing HVIP drayage voucher amount of $150,000 per truck, along with any other applicable HVIP voucher enhancements. This means that in some cases, a single truck could receive a maximum voucher amount of $250,000. With this substantial funding, the Ports of Long Beach and Los Angeles aim to support the purchase and deployment of up to 800 new zero-emission trucks, further advancing their commitment to a cleaner and more sustainable future for port operations. This initiative not only benefits the environment, but also has the potential to drive economic growth and improve the quality of life in the communities surrounding these vital ports.

In conclusion, the transition to MDHD EVs in regions like the IE presents a complex mosaic of challenges and opportunities, particularly for disadvantaged communities and small to medium-sized businesses. While the shift promises significant environmental and health benefits, its economic implications require careful consideration to ensure an equitable transition. The deployment of government incentives, rebates, and strategic support as seen in the Inflation Reduction Act, California's HVIP, and local initiatives like the AQMD's Voucher Incentive Program and the Ports of San Pedro incentives, are crucial in mitigating the financial burden on these communities and businesses. These measures, combined with ongoing efforts to enhance EV infrastructure, workforce training, and legal protections, underline the importance of a multifaceted approach to address the diverse needs of all stakeholders. As the MDHD EV market evolves and expands, maintaining a focus on equitable access and support will be key in achieving a sustainable and inclusive future in transportation and economic development.

Southern California Edison

Southern California Edison's Charge Ready Transport Program offers substantial support for businesses aiming to transition their fleets to EVs. The program covers most costs associated with the installation of EV charging infrastructure, potentially reducing the financial barrier to entry for participants. Additionally, SCE provides special electricity rates designed for EV charging, which feature lower costs during off-peak times. These rates help businesses save on fuel costs when they charge their vehicles during specified lower-rate periods, as illustrated in the uploaded image.

The rates are visually segmented to show off-peak, mid-peak, and on-peak times, clearly outlining when it is most cost-effective to charge EVs. For example, during summer weekdays, off-peak pricing applies from 9 PM to 4 PM, and on-peak pricing applies from 4 PM to 9 PM. In winter, off-peak pricing extends from 9 PM to 8 AM, with super off-peak pricing beneficially set from 8 AM to 4 PM, and mid-peak pricing from 4 PM to 9 PM.

Businesses participating in the program can also take advantage of various incentives to further lower their upfront and operational costs. These include rebates and grants from federal, state, and local sources, such as the California Volkswagen Environmental Mitigation Trust, which allocates about $423 million for eligible "scrap and replace" projects. Moreover, SCE's program includes a Make-Ready Rebate, which covers a significant portion of the infrastructure installation costs if businesses opt to manage the customer-side make-ready work themselves.

To qualify for these benefits, businesses must be SCE customers and commit to purchasing or leasing at least two medium- or heavy-duty battery-powered EVs. They must also own or lease the property where the chargers are installed and agree to operate and maintain these chargers for a minimum of ten years. Additionally, participants are required to provide data on charging equipment usage for at least five years and comply with other program-specific terms and conditions.

7. Business Considerations for Opportunity Charging

7.1 Introduction

This section on Business Considerations for Opportunity Charging investigates the distinct infrastructural and functional aspects of depot and opportunity charging for MDHD EVs. It explores the differences in deployment, power levels, and locations of charging infrastructure for these two charging methods. It also explores the opportunity charging that might be a solution for quick charging during short intervals, offering a means to extend the range or maintain charge levels of MDHD EVs. This section further discusses the technologies involved in opportunity charging, including static and dynamic systems, and outlines the challenges and opportunities associated with these charging methods. The discussion encompasses environmental and economic implications, the role of charging infrastructure in MDHD EV operations, and the broader context of electric mobility, particularly focusing on how these charging strategies support operational efficiency and range assurance for MDHD EVs.

7.2 Defining Depot and Opportunity Charging

The infrastructure for depot and opportunity charging can vary significantly, as they serve different purposes and have different requirements. While there may be some overlap in the types of charging equipment used, the deployment, power levels, and locations of charging infrastructure can differ substantially (US Department of Energy, 2023).

Depot charging is primarily designed to provide a full charge to MDHD EVs over a relatively extended period, often spanning several hours. Depots or central facilities are used by electric buses, delivery trucks, or fleets that return to depots between shifts and use opportunity charging during their layovers. It is typically used for planned charging sessions when the vehicle is not immediately needed, such as overnight charging at home, workplace charging, or scheduled charging at dedicated public charging stations. The depot charging infrastructure encompasses Level 3 DC and sometimes slower AC chargers (Yilmaz & Krein, 2013), making them suitable for longer charging sessions. It is typically employed for planned charging sessions, such as overnight charging at home, workplace charging, or scheduled charging at dedicated public or private charging stations, with the primary aim of providing a full charge to the MDHD EVs over an extended period, often spanning several hours. New initiatives developed by companies and current fleet owners are utilizing these technologies.

> "Our calculation right now is about charging up to six hours before to use the truck next day."
> *Private Sector*

Depot charging includes various methods, such as Direct Current Fast Charging, designed to deliver high-voltage direct current (DC) directly to the MDHD EV battery, ensuring rapid charging. Other methods include Ultra-Fast Charging which provides significantly faster charging, making it suitable for situations where MDHD EV drivers need to quickly add a substantial amount of range in a short time. DC fast chargers, while faster than Level 2 chargers, have lower power levels compared to ultra-fast chargers and are typically used for shorter charging sessions (Abbasi & Zhang, 2021).

In the realm of electric mobility, especially for MDHDVs, there exists a critical challenge of ensuring adequate range while maintaining operational efficiency. This challenge is compounded by the need to avoid prolonged depot charging times. In this context, the integration of opportunity charging presents a viable solution. Opportunity charging, which entails fast charging a vehicle's battery during brief intervals when it is not in operation, emerges as a promising solution for electric mobility of the MDHD fleet.

The following is a list of technologies that are used in opportunity charging. There are two types of opportunity charging. Static opportunity charging refers to charging methods that are stationary, and where vehicles are charged at specific locations such as depots or designated parking spots. Dynamic opportunity charging, on the other hand, refers to charging methods that allow vehicles to charge while in operation or at frequent intervals along their route without significant deviation from their daily operations.

Opportunity charging for MDHDVs involves the practice of strategically charging during brief periods of downtime or stops, as opposed to adhering to pre-scheduled charging sessions at specific stations. This approach harnesses existing infrastructure whenever the truck is momentarily parked, such as during breaks, loading/unloading, or waiting times (Estrada et al., 2017). The efficient scheduling of MDHD EV charging delivers economic benefits to various stakeholders in the energy market (Patil & Kalkhambkar, 2020), and they also serve as valuable grid resources, resulting in reduced energy and maintenance costs for operators. However, a significant challenge that could impede the attainment of these zero-emission truck goals is the absence of a robust charging infrastructure system. Overcoming this barrier is essential, as it holds the key to unlocking substantial environmental and socio-economic benefits. The Opportunity charging system plays a pivotal role in the significance of EV infrastructure for MDHD EVs. Together, they facilitate the seamless integration of electric trucks into the transportation ecosystem (Mahesh et al., 2021).

Static Opportunity Charging:

- **Plug-In Charging Stations:** These are like the charging stations used for passenger EV but are designed for faster charging rates to support the larger battery capacities of trucks and buses. Vehicles need to be plugged in manually (Al-Saadi et al., 2021a; Farzam Far et al., 2022; Mishra et al., 2022a; Zhu et al., 2023).

- **Inductive Charging:** Uses electromagnetic fields to transfer energy between coils placed in the ground and on the vehicle's underside. The primary coil in the ground creates a magnetic field, which induces a voltage in the secondary coil on the vehicle, leading to the charging of the battery. Since there is no physical connection, this method reduces wear and tear (Al-Hitmi et al., 2020; Al-Saadi et al., 2021b; Mishra et al., 2022b; Sacchi et al., 2021a).

- **Battery Swapping Stations:** Although not strictly "charging," battery swapping is a method where depleted batteries are quickly replaced with fully charged ones. This can be especially efficient if the vehicle needs to get back on the road quickly (Jahangir Samet et al., 2021a; Noto & Mostofi, 2023; Ribberink et al., 2021; Wu et al., 2021).

- **Automated Fast Charging Systems:** Robots or automated systems are used to connect the vehicle to the charger. This is a newer development, but it is being explored to reduce manual intervention and speed up the charging process (Danese et al., 2021a; Jahangir Samet et al., 2021b; John et al., 2020; Zhu et al., 2020).

- **Hybrid Systems:** Some systems might combine, for instance, overhead pantograph charging with plug-in capabilities, allowing for flexibility in where and how the vehicle is charged.

- **Destination Charging:** This is not specifically discussed in the literature review, but it generally refers to the practice of charging trucks at their destination or stops along their route. It is a way to utilize the downtime of the vehicle for charging, without requiring extra time specifically set aside for this purpose.

- **Flash Charging:** Daimler Trucks is developing a "future-proof" charging site that includes the potential for 1+ MW chargers. This is part of the wider push for a network of "Mega charger" stations suitable for HDVs, as outlined in the Megawatt Charging System (MCS) standard. That standard focuses on vehicles such as Class 6–8 commercial vehicles with large battery packs capable of accepting more than 1 MW charge rates.

Dynamic Opportunity Charging:

- **On-route Charging:** The current EV charging standards for MDHDVs accommodate slower charging, typically over a few hours. However, on-route charging, which can be implemented at travel plazas or fleet depots, demands charging capacities of up to multiple megawatts.

- **Pantograph Charging Systems:** This involves an overhead system. The EV is equipped with a pantograph (either mounted on the vehicle or on the infrastructure) that can connect to an overhead charging point. When the vehicle is parked beneath the charging point, the pantograph raises to make contact and begins charging (Al-Saadi et al., 2021a; Farzam Far et al., 2022; Mishra et al., 2022a; Zhu et al., 2023).

- **On-Route Charging:** This integrates charging infrastructure into the regular route of the vehicle. Buses, for instance, might have charging stations at bus stops or terminals. They can then charge every time they make a scheduled stop, ensuring the battery never runs too low (Al-Hanahi et al., 2021a; Bal & Vleugel, 2018; Danese et al., 2021b; Sacchi et al., 2021b).

- **Mobile Charging Units:** These are portable charging units that can be brought to a vehicle, useful if it is parked in a location away from its regular charging station or in emergencies (Al-Hanahi et al., 2021b; Jung et al., 2021; Sacchi et al., 2021c; Tong et al., 2015).

Opportunity charging is tailored for quick, on-the-go charging during brief stops or layovers to extend an MDHD EV's range or maintain its charge level. The goal is to provide a partial charge in a short timeframe—often just minutes. This explains why opportunity charging infrastructure typically includes fast-charging stations, such as DC fast chargers, which can deliver high power levels quickly (Guo et al., 2016). It also includes wireless charging (Mahesh et al., 2021) and battery swapping (Ahmad et al., 2020). The choice of technology for opportunity charging may depend on factors such as the charging speed required, the infrastructure available at charging locations, the specific MDHD EV models in use, and cost considerations. However, since opportunity charging is designed to provide a partial charge in a short timeframe, DC fast charging and ultra-fast charging seem best suited for opportunity charging (Neaimeh et al., 2017; Zhou et al., 2020). Note that ultra-fast charging stations, characterized by their significantly higher power levels, often entail more substantial installation expenses compared to DC fast chargers. The necessity of upgrading electrical infrastructure to accommodate the heightened power demand can result in considerable costs. Furthermore, ultra-fast chargers, due to their superior power output and advanced technology, generally involve higher acquisition and installation expenditures relative to DC fast chargers. Finally, both DC fast charging and ultra-fast charging stations may impose access fees or session charges, which can contribute to the overall cost of usage (Hawkins et al., 2013; Neaimeh et al., 2017).

> "I think things are going to change pretty fast and the hard part is for people to make big investments in infrastructure, knowing that something might change in the future."
> *Private Sector*

The expansion of DC fast-charging networks for EVs presents considerable challenges to the stability and reliability of the electrical grid, necessitating a range of innovative solutions. "Smart charging systems," which include features like security and smart metering, are essential for ensuring that MDHD EVs are beneficial to the smart grid (Babar & Burtch, 2023). Additionally, the integration of battery energy storage systems with DC fast chargers helps reduce peak power demand on the grid (Potoglou et al., 2023). Addressing the grid impact of MDHD EV charging stations, especially on weaker AC grids, involves developing and evaluating specific system architectures and control structures (Ahmad et al., 2020). Furthermore, load management strategies using energy management systems with charge scheduling algorithms are crucial for reducing grid stress during peak load times (Liimatainen et al., 2019). Grid upgrades, such as enhancing transformers and integrating renewable energy sources, are also vital for accommodating the additional load from MDHD EV charging stations (RMI, 2023). Finally, demand response programs, which adjust power demand by incentivizing reduced electricity use during peak times, play a significant role in managing the grid load (Verbrugge et al., 2023). These multifaceted approaches underscore the importance of advanced technology and strategic planning in sustaining the growth of MDHD EVs while ensuring the reliability of the electrical grid (Babar & Burtch, 2023).

The coexistence of depot and opportunity charging facilities at the same locations presents a flexible and convenient arrangement for MDHD EV users. This is particularly beneficial in scenarios where a charging station serves dual purposes. MDHD EV users can also take advantage of public charging stations for quick top-offs or to extend their range during travel when a full charge is not needed (Van der Horst et al., 2023).

Regardless of whether one uses depot charging or opportunity charging, the challenge of charging MDHD EVs is complex. In addition to the different types of power MDHD EVs are using, the use of different types of connectors for charging is an additional challenging layer (Raff et al., 2019). MDHD EVs have various charging standards (Das et al., 2020). Ensuring that drivers can use charging stations across different networks (roaming) and that charging equipment from different manufacturers can work together (interoperability) are ongoing challenges (Van der Horst et al., 2023).

7.3 Why and When Do We Need Opportunity Charging

There has been a notable increase in the adoption of electric trucks, particularly in the MDHD segments, driven by support for ZEVs and advancements in battery technology. Medium-duty electric trucks typically feature battery capacities ranging from 48.5 kWh to 350 kWh, providing a range of up to 250 miles. On the other hand, heavy-duty electric trucks boast capacities ranging from 120 kWh to 1000 kWh, offering a range of up to 500 miles (Liu et al., 2019).

The suitability of current MDHD EV models to cover the daily travel distance of commercial vehicles depends on the estimated range of the MDHD EVs and the availability of compatible charging infrastructure (Forrest et al., 2020). Surveys conducted by the National Renewable Energy Laboratory (2017) and the North American Council for Freight Efficiency (2022) reveal that the majority of medium-duty commercial vehicles typically cover an average daily travel distance of 80–250 miles, whereas heavy-duty commercial vehicles can reach distances of up to 700 miles. Consequently, the reported range of MD EVs can effectively cover a significant portion of the daily travel distance with a single charging session per day, particularly at locations where they park overnight or during shift changes (Liimatainen et al., 2019).

Commercial fleet operators can strategically plan charging schedules to optimize the utilization of their MDHD EVs, ensuring their availability for intended routes without unnecessary downtime. Regular charging is typically employed for planned charging sessions, like overnight charging at home, workplace charging, or scheduled charging at dedicated public charging stations. The primary objective is to provide a complete charge to the MDHD EVs over an extended period, often spanning several hours.

Opportunity charging becomes indispensable in certain scenarios, especially for MDHD EVs such as delivery trucks and buses, which may encounter unforeseen disruptions to their routes, necessitate additional stops due to customer requests, contend with traffic congestion, or face unexpected emergencies. In such instances, the strategic placement of opportunity charging stations along the route becomes imperative to mitigate the risk of depleting the battery's charge (Zhou et al., 2020). Moreover, drivers may occasionally grapple with concerns about running out of charge before completing their routes, particularly in regions where charging infrastructure is sparse. In such instances, opportunity charging steps in to alleviate range anxiety by swiftly providing an energy boost when needed (Pevec et al., 2020).

> "So, like certain companies are able to have a fixed route return to base operation, I think in that instance you know obviously more traditional charging may work for them, but it is not the case for all, I think is clear trucking companies need several options when it comes to charging, because something can always come up."
>
> *Private Sector*

Strategically positioned charging stations are integral components of charging infrastructure: they are strategically located along well-traveled routes, including highways, major roads, and urban areas—precisely where MDHD EV drivers tend to frequent. The selection of charging locations is driven by a profound understanding of common travel patterns and preferred destinations for EV users. Notably, they are often conveniently situated near popular rest stops, shopping centers, or key transit hubs, ensuring that recharging opportunities are seamlessly integrated into the travel experience (Kizhakkan et al., 2019; Zhao et al., 2019). This network of strategically placed opportunity charging stations effectively serves as a bridge between planned charging sessions, providing a lifeline for MDHD EV drivers when a nearby charging station is not readily available. The user experience of MDHD EVs is shaped by various operational and economic factors. The total cost of ownership (TCO) for MDHD EVs is a significant consideration, requiring competitiveness with diesel vehicles. While the purchase price of MDHD EVs is higher, the maintenance costs are generally lower. However, charging station installation can be costly, and recharging costs depend on fluctuating electricity tariffs (Vaidya et al., 2023). Operationally, MDHD EVs face challenges in range, recharge time, and payload capacity. These vehicles typically have a range below 200 miles, considerably less than diesel vehicles, and require longer recharge times.

> "So, they work for us just based upon what's available out there in the truck battery pack range, we will definitely want to take advantage of some opportunity charging."
>
> *Public Sector*

This necessitates the availability of public charging stations for fleets without depots and affects the total cost relative to diesel (Resources for the Future, 2023).

Infrastructure requirements for MDHD EVs are extensive. Charging these vehicles, especially for large fleets, may demand significant power and could destabilize electricity distribution systems. Investment in the grid, transmission systems, and generation capacity is needed to support this demand. Moreover, the unpredictability of MDHD EV traffic flows and load requirements poses challenges for grid stability (Shafiei & Ghasemi-Marzbali, 2022).

Policies aimed at promoting MDHD EV adoption include subsidies to lower upfront costs and initiatives to manage operating costs effectively. Electricity tariffs, low-carbon fuel standards, vehicle-to-grid contracts, and co-located solar and storage options are strategies to make MDHD EVs more affordable and environmentally sustainable.

Efforts to improve on-route charging, deal with externalities, and increase adoption by small fleets are also critical. Policies need to address the challenges of long charging times and the environmental impacts of increased electricity demand while providing technical and financial support to small fleets and those in environmental justice communities.

The intricacy of the MDHD EV charging ecosystem is significantly influenced by regulatory and policy frameworks. Government regulations and policies play a pivotal role in shaping the MDHD EV charging infrastructure, providing incentives, and ensuring efficient integration with the electrical grid (California Energy Commission, 2023). These factors not only impact the development and accessibility of charging stations, but also influence the overall user experience. Regulatory measures determine key aspects such as charging standards, safety protocols, and grid connectivity, while policy incentives can drive the economic feasibility and market penetration of MDHD EVs (Mastoi et al., 2022a). The effective implementation of these regulations and policies is crucial in overcoming operational challenges like range limitations, recharge times, and infrastructure demands. Moreover, they are essential in addressing broader issues such as environmental sustainability, grid stability, and equitable access to charging solutions, all of which directly affect the user experience and acceptance of MDHD EVs. The current landscape of standardization in MDHD EV charging infrastructure is at an early stage, marked by significant regional disparities in terms of availability and accessibility.

One of the major challenges in the deployment of MDHD EV charging infrastructure is the lack of standardization in charging technology, which impedes the compatibility between manufacturers' vehicles and charging stations. This absence of standardization results in difficulties for manufacturers in producing EVs and charging stations that are universally compatible (Das et al., 2020).

In terms of specific standards, the SAE J1772 standard, developed by the Society of Automotive Engineers in 2009, is a crucial protocol in the MDHD EV charging industry. It is a protocol that ensures MDHD EVs can be safely and reliably charged from compatible charging stations. This standard is both a physical and electrical connection standard, defining connectors, cables, and electrical signals to control the flow of electricity between the vehicle and the charger. It is widely used globally and is essential for ensuring that EVs can be charged safely and reliably from any compatible charging station (Bommana et al., 2023). Smart charging generally refers to a system that intelligently manages the charging of MDHD EVs, optimizing for factors such as grid load, charging costs, and user requirements. This can include technologies like vehicle-to-grid (V2G) integration and demand-response mechanisms (Kubli, 2022).

Alternatively, the SAE J3271 standard, also known as the Megawatt Charging System (MCS), represents a significant advancement in charging technology for MDHD EVs. Designed to meet the unique demands of larger commercial vehicles that require rapid recharging to minimize downtime, MCS can provide extremely high-power charging. This is crucial for vehicles such as Class 8 tractors, where a 1.6-MW charge is needed to recover 400 miles of range within a 30-minute break. The development of SAE J3271 follows a structured process, progressing from a technical information reference to a recommended practice, and finally to an industry standard. The standard encompasses not just the power delivery, but also standardized coupler design, communication protocols, and safety requirements, ensuring interoperability across vehicles, charging stations, and the electric grid.

The J3271 standard is set to complement rather than replace the existing J1772 Combined Charging System (CCS), effectively taking over where J1772 CCS ends in terms of charging power. This marks a significant step in the evolution of EV charging infrastructure, particularly catering to the commercial sector where rapid and high-power charging is essential. The introduction of the MCS under the J3271 standard is a clear indicator of the evolving landscape of EV technology, addressing the specific needs of heavy-duty EVs in the commercial domain.

7.4 Stages and Technologies in Opportunity Charging

The opportunity charging process consists of several essential steps. It commences with the detection and connection phase, which is followed by the authentication and payment phase. Opportunity charging also implies a charging protocol and a clear charging duration. Additionally, the process incorporates robust safety measures and monitoring systems to ensure a secure charging experience.

The detection and connection phase is a focal point, particularly when considering both wired and wireless (non-wired) connections. This phase is crucial for ensuring the efficiency, safety, and reliability of the charging process (Palani et al., 2023). The detection and connection phase in wired systems involves physical connectors and standardized protocols, with research focusing on developing robust connectors for high power levels and ensuring reliable communication between the vehicle and the charger (Johnson et al., 2022). In contrast, wireless systems in this phase involve more complex processes like inductive or resonant charging technologies, where alignment and communication protocols are key areas of study (Saini et al., 2023).

For wired connections, the physical plugging in of the charger is a critical aspect, with research exploring automated connection systems to ease the process for MDHD EVs. Wireless connections, however, focus on achieving optimal alignment between coils and initiating charging without a physical connection, with studies delving into automated parking assistance and real-time adjustment mechanisms (Suriya & Shankar, 2022).

The parties involved in authentication include the MDHD EV driver or user, the charging station's authentication system, and the charging network or service provider (ElGhanam et al., 2021). The most common authentication methods often include the following: (1) RFID Cards: Users may have RFID (Radio-Frequency Identification) cards. The station reads the RFID information and verifies it against a database of authorized users; (2) Mobile Apps: Many charging networks offer mobile apps that allow users to initiate charging sessions. Users log in to the app, and their identity is verified through their account credentials (Energy Your Way, 2023); (3) Payment Cards: Some charging stations allow users to start a session by swiping a payment card (credit or debit card) (Wolbertus et al., 2018); and (4) PIN Codes: PIN code authentication at electric vehicle charging stations allows users to start charging sessions by entering a PIN. This secure method is often integrated with software systems for additional functionalities like customer billing and charger monitoring.

Payment involves finalizing the expenses incurred for the electricity used during the charging session (Potoglou et al., 2023). The available payment options vary based on the charging station and network. These methods often include: (1) Pay-as-You-Go: Charges are calculated based on the electricity consumed and the applicable rate (LaMonaca & Ryan, 2022); (2) Subscription Models: Some charging networks employ a subscription plan where users pay a monthly fee; (3) Membership Cards: Users may have membership cards or accounts linked to a prepaid balance; and (4) Roaming Agreements: In cases where users are traveling and need to charge on networks outside their usual service area, for example, roaming (Priyasta et al., 2022).

According to Stillwater and Nicholas (2013), the current ecosystem of mobile apps for MDHD EV drivers falls into six primary categories: purchase decisions, vehicle dashboards, charging availability and payment, smart grid interaction, route planning, and driver competitions. Although these apps offer various services, including pre-sale consumer information, charging details, and navigation features specific to MDHD EVs, the market is highly fragmented, with numerous apps offering niche information and utilizing different methodologies. One major challenge is the lack of uniformity and standards between vehicle and charger systems (Stillwater et al., 2013). This results in a barrier to broader app adoption due to the absence of common vehicle and charger APIs (application programming interfaces), data availability, reliability, formats, and proprietary payment and billing methods. Regardless, as the industry evolves and standardization improves, mobile apps are expected to play an even more significant role in enhancing the EV driving experience (OECD, 2021).Charging protocol involves the development and standardization of communication protocols between the MDHD EV and the charging station, such as the combined charging system (CCS). These protocols are crucial for ensuring compatibility across different charging systems and vehicles, and they play a pivotal role in managing power transfer. This management is essential not only for optimizing the charging time but also for maintaining the health and longevity of the vehicle's battery (Utilities One, 2023).

Charging duration is another significant focus, especially given the larger battery capacities and higher energy requirements of MDHD EVs. Opportunity charging is designed to facilitate rapid charging, enabling vehicles to recharge during brief operational breaks. This rapid charging capability is crucial in minimizing vehicle downtime and enhancing operational efficiency, a key consideration in commercial and industrial applications (Energy Your Way, 2023).

Safety in the charging process is paramount. Research in this area concentrates on ensuring adherence to stringent electrical safety standards to prevent hazards such as electric shocks or fires. Additionally, there is a focus on developing systems to monitor the battery's temperature and state of charge, thereby preventing issues like overcharging or thermal runaway, which are particularly pertinent concerns in larger battery systems (Chen et al., 2021).

Finally, continuous monitoring during the charging process is critical. This involves real-time tracking of various parameters, including the charging rate and battery temperature. Advanced monitoring systems are being developed to provide immediate alerts for any irregularities and to dynamically adjust charging parameters. This real-time adjustment is vital for optimizing the charging process, ensuring both the safety and efficiency of the charging operation (Jiang et al., 2021).

7.5 A Strategic and Sustainable Infrastructure Investment

MDHD EVs generally exhibit lower operating costs in comparison to their diesel or gasoline counterparts. This encompasses reduced fuel expenses, decreased maintenance outlays owing to the fewer moving components, and the potential for tax incentives to encourage the adoption of electric fleets. Furthermore, MDHD EVs offer the advantage of being quieter than conventional trucks, thereby mitigating noise pollution and contributing to a more serene urban environment (Ahmad et al., 2020). In addition to these benefits, MDHD EVs hold the potential to enhance grid management, with grid operators collaborating with fleet managers to optimize charging schedules and ensure that the charging infrastructure does not strain the local power grid (Hossain et al., 2022). Lastly, the development, installation, and maintenance of EV charging infrastructure are expected to create job opportunities across various sectors, including construction, electrical services, and technology (Johnson et al., 2022).

Investing in MDHD EV charging stations offers a range of advantages for businesses, and these benefits extend well beyond the potential return on investment (ROI). By offering a convenient charging solution, businesses can foster trust and loyalty among their customers, thereby increasing foot traffic and customer engagement (Babar & Burtch, 2023). Furthermore, providing MDHD EV charging stations demonstrates a commitment to sustainability and environmental responsibility, which is increasingly important in today's eco-conscious society. This dedication to sustainability can also serve as a compelling selling point for businesses, enhancing their brand image and attracting environmentally conscious consumers (Shafiei & Ghasemi-Marzbali, 2022). In addition to these customer-centric benefits, there are financial incentives for businesses to deploy MDHD EV charging stations. Certain federal and state incentives offer tax credits that can substantially offset the installation costs (Arlt & Astier, 2022).

However, the decision to invest in MDHD EV charging stations must be carefully evaluated, taking into consideration the complexities of the return on investment (ROI). The ROI for MDHD EV charging stations is influenced by various factors, including geographical location, the density of EV owners in the area, and the choice of charging standard. It is important to note that the ROI for MDHD EV charging stations may require a longer timeframe, potentially up to four years or more, to recoup the initial capital investment. Nevertheless, over the long term, studies suggest that the ROI can yield positive outcomes, with some indicating a potential return of up to 95% over five years (Mastoi et al., 2022b).

The assumption of risk and the ROI considerations for opportunity charging MDHD EVs can vary significantly depending on the specific charging scenario and the parties involved. For public charging stations, owners typically bear the risk associated with infrastructure, including maintenance, repair, and potential liability issues. The profitability of these stations hinges on factors such as usage rates, pricing strategies, and the initial investment in charging equipment (California Governor's Office of Business and Economic Development, 2023).

In contrast, in the case of private charging stations (such as workplace charging), employers or property owners generally assume the risk and costs related to installation, maintenance, and potential liability. While this arrangement may not always have a direct financial return like public charging stations do, it can bring benefits such as increased employee satisfaction, retention, and attraction (Tan et al., 2023).

It is crucial to recognize that the risk and ROI considerations for opportunity charging are influenced by various factors, including the type of charging station, its location, utilization rates, pricing models, and regulatory environments. Additionally, partnerships and collaborations among different stakeholders can play a significant role in determining how risk and ROI are distributed.

To address the ROI of MDHD EVs, several studies highlight key factors and projections. The U.S. Department of Energy (DOE) projects that by 2030, nearly half of MDHD EVs will be cheaper to buy, operate, and maintain compared to diesel trucks. By 2035, electric MDHD EVs are expected to be cost-competitive with diesel trucks, especially for models with less than a 500-mile range. Hydrogen fuel cell EVs are also projected to become cost-competitive for long-haul heavy-duty trucks by 2035 (DOE, 2022).

In conclusion, investing in MDHD EV charging stations offers businesses an array of benefits, including enhanced customer trust, loyalty, and environmental responsibility. While the ROI may be complex and require a longer timeframe to materialize, the potential for positive financial outcomes and various non-financial advantages make MDHD EV charging stations a viable and strategic investment. Additionally, strategic considerations should include the long-term viability of the charging stations, ensuring they can adapt to future technological advancements and increasing demand. Careful evaluation and consideration of risk factors, alongside an understanding of the specific charging scenario, are essential for making informed investment decisions in this evolving industry (Energy Your Way, 2023).

7.6 Private Sector Interviewees

The thematic analysis conducted through qualitative interviews reveals a complex and intricate landscape of opinions in the private sector.

A principal theme that emerges is the disparate levels of awareness and understanding among private sector entities. This disparity is characterized by a split where some respondents exhibit a conspicuous deficit in comprehending the nuances of the transition and its regulatory environment, especially in small businesses and owner-operators. In contrast, others demonstrate heightened awareness, often facilitated through proactive communications from entities. The private sector expresses apprehension regarding the dynamic nature of regulatory frameworks in California, with a specific focus on port regulations. This theme highlights an acute awareness of the ever-evolving regulatory landscape and its potential implications on the transition, underscoring the sector's need for regulatory predictability and stability. This theme encapsulates a commitment to adhering to state regulations, coupled with skepticism and concerns, particularly regarding charging infrastructure. Concurrently, the emphasis on the role of education in facilitating the transition points to a recognition of the need for capacity building and knowledge dissemination.

Financial aspects, particularly the cost implications of electric trucks and the availability of grants, emerge as a significant theme. This concern is indicative of apprehension regarding the economic viability and sustainability of the transition, reflecting a critical assessment of the financial underpinnings necessary for a successful transition. The theme of proactiveness is discernible, with certain respondents positioning themselves as pioneers in embracing the transition. This forward-thinking stance is emblematic of a segment within the private sector that is not just responsive but anticipatory of the impending changes.

A diverse array of opinions regarding the transition's feasibility is captured through the interviews. It encompasses skepticism, an acknowledgment of initial challenges, positive outlooks, and a recognition of the transition's potential benefits, illustrating the sector's multifaceted viewpoints. Acknowledgment of the need for robust charging infrastructure is contrasted with concerns about the operational feasibility of integrating charging processes into daily business operations, such as loading and unloading.

Financial and supply chain considerations are foregrounded in interviewees' remarks, alongside an acknowledgment of the challenges and the necessity for adaptive strategies. However, discussions on the environmental benefits of EVs are notably less prominent. The workforce development theme reveals the presence of diverse training efforts within companies, encompassing in-house programs and external collaborations, and the sector's investment in human capital development in response to the transition within big companies. However, small and medium-sized companies are far from having any readiness for the transition.

7.7 Takeaways

In conclusion, the exploration of opportunity charging for MDHD EVs in a business context reveals a complex interplay of technology, economics, and operations. Distinguishing between depot and opportunity charging highlights their unique infrastructural and operational needs. Opportunity charging, with its advanced technologies such as inductive charging and automated charging systems, addresses range anxiety and operational efficiency challenges, offering rapid charging solutions during operational downtimes.

Investing in opportunity charging infrastructure aligns with environmental sustainability and efficient grid management, offering businesses both economic benefits and a platform to showcase environmental responsibility. However, such investments require careful consideration of factors such as location, usage rates, and charging standards to ensure a viable return on investment.

Part V: Discussion, Recommendations, and Conclusions

8. Discussions & Recommendations

8.1 Synthesis of Key Findings

The transition to MDHD EVs in the IE represents a significant shift in transportation dynamics with profound economic, environmental, and social impacts. This change is driven by a growing recognition of the need for sustainable transportation solutions to address environmental concerns, particularly air pollution and greenhouse gas emissions attributed to the heavy reliance on diesel and gasoline-powered vehicles in the region. The implementation of MDHD EVs is poised to offer substantial environmental benefits, including a reduction in local air and noise pollution and contributing to improved public health outcomes. These benefits are especially pertinent in the IE, where disadvantaged communities have historically borne the brunt of industrial and vehicular emissions.

This shift is particularly crucial in disadvantaged communities, which are disproportionately affected by vehicular emissions. The anticipated improvement in air quality could lead to enhanced health outcomes in these areas. The transition's success hinges on the ability of these enterprises to adapt financially and operationally to the new electric-focused transportation paradigm. Addressing these disparities requires a holistic approach that integrates inclusive policymaking and ensures that the benefits of this transition are equitably distributed,

The operational efficiency of MDHD EVs, a key concern for businesses, is intricately linked to the development of adequate charging infrastructure. Depot charging offers a solution for longer charging sessions, often overnight, making it suitable for vehicles returning to a central location. Alternatively, opportunity charging presents a strategic approach to extend the operational range and maintain charge levels during short intervals, such as layovers or loading and unloading times. This method of charging is crucial in addressing range anxiety and ensuring continuous operation without significant downtime. The implementation of these charging strategies is not without challenges, particularly regarding the establishment of robust and widespread charging infrastructure. The expansion of this infrastructure, particularly for opportunity charging, necessitates significant investment in grid capacity and smart charging systems to manage the increased load and ensure grid stability. For instance, the W, N, and NC subregions, characterized by high HDV traffic and significant dwell times, necessitate a focus on depot charging for extended recharge periods. In contrast, the W, SC, and S subregions, with pronounced MDV activity require a more dynamic approach, integrating opportunity charging to cater to their operational rhythms. Opportunity charging increases the daily driving range while maintaining operational efficiency. It is particularly beneficial for enabling multi-shift operations. Conversely, the depot charging strategy reduces operational efficiency. It could lead to significant delays in the transport operation if a suitable charging station is not reached in time. This strategy might be suitable for long-haulers who drive for long hours and long distances.

The economic implications of the transition to MDHD EVs are complex and varied. While the adoption of these vehicles offers lower operating costs compared to their diesel counterparts, the initial investment in the vehicles and charging infrastructure is substantial. Furthermore, the total cost of ownership is influenced by factors such as electricity tariffs, charging station installation costs, and maintenance expenses. Large corporations and forward-thinking businesses are often at the forefront, embracing the transition to enhance their environmental credentials and operational efficiency. For small and medium-sized businesses, particularly in disadvantaged communities, these costs can be prohibitive. Therefore, the availability of government incentives and rebates, as seen in programs like the Inflation Reduction Act and California's HVIP, is crucial in mitigating the financial burden of transitioning to MDHD EVs. These incentives help not only in offsetting the high upfront costs but also in making the long-term operation of MDHD EVs economically viable. In the end, these factors can have a significant impact on the financial implications and profitability associated with the use of MDHD EVs, a critical consideration in fleet decision-making. Strategies that enhance MDHD EVs' capabilities can enhance the overall value of the purchase. However, there is a trade-off, as operational costs, including energy and maintenance expenses, may rise due to increased charging requirements and accelerated battery degradation. Businesses must factor in these higher operational costs when evaluating the long-term financial viability of MDHD EV charging stations. Additionally, the reliability of emergency charging strategies poses significant challenges. Emergency charging infrastructure needs to be robust and widespread to prevent operational disruptions, which requires careful planning and substantial investment. Furthermore, accelerated battery degradation could lead to higher replacement costs and downtime, affecting overall fleet efficiency. Addressing these challenges involves staying updated with technological advancements, implementing regular maintenance schedules, and potentially investing in on-site renewable energy sources to offset energy costs. By thoroughly considering these factors, businesses can better prepare for the complexities of integrating MDHD EV charging infrastructure and ensure a smoother transition.

In conclusion, the shift to MDHD EVs in the IE is a multifaceted endeavor that demands a coordinated approach encompassing environmental considerations, economic viability, infrastructural development, and equitable access. The success of this transition hinges on the ability to balance these diverse yet interrelated factors, ensuring that the move towards electric mobility is sustainable, economically feasible, and inclusive. This aim calls for strategic collaborations between various stakeholders, including government agencies, private businesses, and local communities, to create a conducive system that supports the widespread adoption of MDHD EVs and the realization of their full potential in terms of environmental benefits and operational efficiency.

8.2 Comparative Analysis of Interviewees

The private sector prominently focuses on the challenges associated with charging infrastructure, underscoring the critical nature of this aspect for a successful transition. Additionally, there is a pronounced emphasis on the importance of training and education, contrasted with a notable deficiency in existing training initiatives. This sector also highlights significant concerns about infrastructure, aligning closely with its apprehensions about the financial implications of the transition. Conversely, the government sector parallels the business sector in emphasizing the importance of charging infrastructure but diverges in its greater emphasis on the lack of training initiatives. This sector also underscores the importance of training and education, albeit with a notable focus on collaborative efforts. Furthermore, the government sector uniquely highlights the necessity for financial support, reflecting its role in policy and regulation shaping.

Both sectors exhibit a mix of optimism and concern in their sentiments toward the transition. The private sector acknowledges the transition's importance but expresses concerns about infrastructure and financial constraints. The government sector mirrors this sentiment, balancing the recognition of the transition's importance with challenges in training and infrastructure.

Charging infrastructure emerges as a central concern in both sectors, with mixed opinions on the feasibility of opportunity charging. Training and support are identified as crucial elements, with both sectors acknowledging a lack of training initiatives and the necessity for diverse support. Challenges and opportunities are recognized by both, with infrastructure and training as recurring themes, alongside the acknowledgment of potential benefits in the transition.

In summary, the comparative analysis illuminates both shared and distinct concerns and perspectives within the private and public sectors regarding the transition to MDHD EVs. The private sector's discourse is heavily centered around infrastructure and financial concerns, while the government sector places a stronger emphasis on policy, regulation, and collaborative efforts. Despite their differences, both sectors agree on the need for enhanced training, support, and better infrastructure to facilitate a successful transition.

8.3 Possible Opportunity Charging Scenarios

The IE, a bustling region known for its economic activity and diverse transportation needs, presents a multitude of scenarios for static opportunity charging. These scenarios span urbanized areas with high-density business zones to suburbanized and rural remote regions with distinct charging requirements. Understanding the varied charging types and infrastructure demands in these scenarios is crucial for optimizing the efficiency and effectiveness of the charging network. This summary will delve into the intricacies of each scenario, providing insights into the charging technologies, locations, and infrastructure considerations tailored to the unique characteristics of each area.

Static Opportunity Charging Scenarios

Rural Areas

Rural Hub Swap Stations:

- Install battery swapping stations along popular LH routes for MDHDVs; ideal for quick battery exchanges.

- Place these stations near centralized hubs or truck stops where vehicle traffic is higher, ensuring minimal downtime for vehicles requiring rapid service.

Remote Flash Charging Sites:

- Develop high-capacity flash charging stations in industrial zones where HDVs are predominant, facilitating rapid cargo turnover.

- Target areas with higher dwell times, such as mega hubs or logistics centers, to provide quick charging solutions and offset longer wait times.

Eco-Friendly Hybrid Stops:

- In areas with a mix of MDV and HDV traffic but limited infrastructure, establish hybrid charging stations that offer both traditional plug-in and renewable energy-powered charging options, like solar-assisted stations, to cater to the diverse requirements of passing vehicles.

Suburban Areas

Suburban Inductive Logistics Hubs:

- Implement inductive charging at distribution centers and warehouses where trucks have scheduled stops, streamlining the charging process without disrupting logistics operations.

- Optimize for regions with a mix of high HDV traffic and moderate MDV activity to serve the varied needs of vehicles.

Destination Charging Networks:

- Set up destination charging points in commercial zones and at final delivery points for long-haul trips where trucks can capitalize on longer dwell times for charging.

- Utilize available lots near distribution centers and retail outlets for these installations, accommodating multiple trucks simultaneously.

Suburban Smart Charging Grids:

- Create a network of smart charging stations in residential zones that adjust charging rates based on grid demand and vehicle usage patterns, providing a balance between residential electricity needs and the requirements of the local MDV and HDV fleets.

Urbanized Areas

Urban Core Plug-In Stations:

- Integrate plug-in charging stations within urban hubs, focusing on areas with high business-centric land use and dense transportation and warehouse facilities.

- Leverage existing truck parking infrastructure to create a network of charging stations that cater to MDVs with high fleet registrations and areas with high megawatt and voltage capacity.

High-Efficiency Hybrid Systems:

- Deploy hybrid charging systems combining plug-in and pantograph options in mixed-use depots serving a diverse range of trucks.

- Focus on areas with high average dwell times and truck counts to offer flexible and efficient charging solutions for both MDVs and HDVs.

Centralized Automated Fast Charging Hubs:

- In urban areas with heavy traffic congestion and high dwell times, install centralized automated fast charging hubs that can service multiple vehicles simultaneously, reducing wait times and increasing throughput during peak operational hours.

Dynamic Opportunity Charging Scenarios

Rural Areas

Rural Travel Plaza Charging:

- On-route charging at travel plazas along highway exits for regional short-haul trips.

- High fleet registration areas with existing truck parking facilities.

- High megawatt and voltage capacity for quick top-ups.

Remote Pantograph Charging:

- Pantograph Charging Systems at cargo inspection points or agricultural depots.

- Low HD traffic areas with predictable dwell times.
- Situated on vacant land with limited electrical grid capacity.

Rural On-Route Bus Depot Charging:

- On-route charging at bus depots or community centers used by rural transit buses.
- High dwell truck count with low business-centric land use.
- Mobile Charging Units deployed as needed for areas with insufficient infrastructure.

Suburban Areas

Suburban Fleet Depot Charging:

- On-route charging at fleet depots for suburban delivery vehicles.
- High MDV traffic areas with moderate business-centric land use.
- Integrated into areas with high density transportation and warehouse facilities.

Suburban Border Crossing Pantograph:

- Pantograph charging for vehicles with scheduled stops at suburban border crossings or checkpoints.
- High HD traffic area with substantial transportation and warehouse businesses.
- High voltage and megawatt capacity for rapid pantograph charging.

Suburban Transit On-Route Charging:

- On-route charging at frequent bus stops within suburban corridors.
- Mixed HD and MD traffic areas with regular but brief stops.
- Areas with high business-centric land use and registered fleet density.

Urbanized Areas

Urban Expressway On-Route Charging:

- On-route charging along urban expressways at service areas for medium-duty delivery trucks.
- High-density transportation hubs with significant fleet registration per area.
- Located in regions with high megawatt and voltage capacity.

Urban Logistics Hub Pantograph:

- Pantograph charging at urban logistics hubs with high dwell truck times.
- High HD traffic areas with robust truck parking infrastructure.
- Charging stations with high voltage and megawatt capacity for quick pantograph charging.

Urban Public Transit On-Route Charging:

- On-route charging at public transit terminals for buses in dense urban areas.
- High dwell count locations, such as central bus stations or busy stops.
- Supported by high-capacity electrical infrastructure for continuous charging throughout the day.

In the dynamic landscape of IE, the implementation of static opportunity charging solutions is paramount to support the diverse demands of urbanized, suburbanized, and rural remote areas. From plug-in charging stations in high-density business districts to battery swapping stations in rural regions, each scenario is meticulously tailored to cater to specific traffic patterns, dwell times, and land use characteristics. As dynamic opportunity charging is explored in the subsequent discussion, it becomes evident that a holistic approach to charging infrastructure development is essential to meet the needs of this thriving region, while promoting sustainability and efficiency in the transportation sector.

8.4 Challenges and Opportunities

A multitude of policy incentives have been introduced with the aim of bolstering the adoption of MDHD EVs within the transportation sector. These incentives are designed to enhance the appeal of MDHD EVs, thus playing a pivotal role in stimulating MDHD EV sales. As illustrated in this report, these incentives can be categorized into two primary domains: financial incentives and non-financial incentives. The financial incentives encompass a range of mechanisms targeting the financial aspects associated with the purchase and utilization of MDHD EVs, and these are implemented through diverse means such as post-purchase rebates, tax exemptions, and income tax credits. Furthermore, financial incentives may also come with non-monetary benefits, including privileges such as free or preferred parking and complimentary charging services. On the other hand, non-financial incentives encompass a wide array of non-monetary advantages extended to MDHD EV owners. These incentives can take the form of initiatives aimed at bolstering charging infrastructure development, raising public awareness, and providing consumers with comprehensive information and education regarding the distinctions between MDHD EVs.

As opportunity charging is a necessity for several scenarios, public charging locations are also an inevitable element of a holistic infrastructure that supports electrification. There is a high need for network density, especially in the W, SC, and NC subregions, to avoid disruptions to MDHD EV operations. It is imperative to minimize any additional personnel costs for MDHD EV drivers in the future. This goal entails strategic planning, including recharging the vehicles during scheduled breaks, minimizing unnecessary detour miles, and avoiding extended waiting times at charging stations. A robust and well-distributed network of public charging infrastructure, along with opportunity charging strategies, plays a pivotal role in addressing this concern. One of the prominent challenges underscored is the complexity of recharging MDHD EVs during regional short haul trips.

8.5 Government Engagement, Policy, and Social Equity

In the context of the electrification of MDHDVs, the role of government in formulating dynamic policies, regulations, and incentives is crucial. Drawing from the experiences of regions like the IE, it is evident that a multifaceted approach, sensitive to the unique needs of various subregions, might substantially enhance the effectiveness of this transition.

A key aspect of this approach could involve the expansion and refinement of financial incentives, such as those exemplified by the Inflation Reduction Act and California's HVIP. These incentives might be more impactful if tailored to the specific needs of small and medium-sized businesses, which often face significant hurdles in financing the transition to electric fleets. Incentive programs could be redesigned to provide more targeted support, potentially including subsidies, tax credits, and grants aimed at reducing the initial cost barriers associated with MDHD EV adoption.

In addressing infrastructural needs, a potential focus area could be the development and standardization of charging technologies and connectors. This standardization could facilitate interoperability between different MDHD EV models and charging systems, simplifying the infrastructure development process, and potentially reducing costs. Additionally, incorporating safety protocols and grid connectivity standards into this framework could ensure the safe and efficient integration of MDHD EVs into existing power grids.

Investments in charging infrastructure, particularly incorporating opportunity charging strategies into policies, are another critical area of focus. These investments might be strategically directed to address the diverse operational patterns of MDHD EVs in different areas. Enhancing grid capacity to support the increased load from electric vehicle charging is also essential. Public-private partnerships could serve as a valuable tool in this regard, enabling governments to leverage private sector investments while providing the necessary regulatory and financial backing.

Furthermore, policies and regulations might also consider the dynamic nature of the MDHD EV market. This includes anticipating future trends in MDHD EV technology, understanding the evolving needs of the transport sector, and being responsive to the environmental impact of these changes. By fostering an environment that encourages innovation and collaboration among manufacturers, energy providers, and end-users, governments could facilitate a more seamless and efficient transition to electric mobility in the heavy-duty vehicle sector.

The transition to MDHD EVs calls for government policies that are not only forward-thinking and inclusive, but also flexible enough to adapt to changing circumstances. Such policies could significantly contribute to the successful and equitable adoption of MDHD EVs, ensuring environmental benefits are realized while supporting the economic vitality of all stakeholders involved in this transformative journey.

9. Conclusions, Limitations, and Future Study

9.1 Conclusions

The comprehensive analysis of the transition to MDHD EVs across diverse subregions yields several key findings that are pivotal in understanding the multifaceted nature of this transformation. Firstly, the transition's impact on different stakeholders, including government bodies, private sector entities, and disadvantaged communities, is profound and varied. For small and medium-sized businesses, particularly in economically constrained areas, the shift to MDHD EVs presents financial challenges, highlighting the need for targeted support and adaptation. In contrast, larger corporations and affluent regions may navigate this transition with more resources and proactive strategies. Communication among all stakeholders is critical in the success of this transition. Even though a number of initiatives exist, more can be done.

Policy and regulatory frameworks emerge as a cornerstone in facilitating the electrification of MDHD EVs. Policies must be dynamic, adaptable, and inclusive, reflecting the distinct needs of various subregions. Financial incentives, like subsidies and tax credits, are crucial in mitigating the higher upfront costs associated with electric trucks, especially for smaller businesses. Furthermore, the standardization of charging technologies and connectors is imperative for reducing infrastructural complexity and cost, ensuring a smoother transition.

Technological advancements in MDHD EVs and their charging infrastructure play a significant role in this transition. The development of both depot and opportunity charging stations is essential to cater to the varied operational patterns across different regions. Enhancements in grid capacity and the integration of public-private partnerships are also vital for supporting the increased demand for electric vehicle charging.

Lastly, the aspect of equity is integral in the transition to MDHD EVs. Disadvantaged communities, often disproportionately affected by vehicular emissions, stand to benefit significantly from the environmental improvements brought about by electrification. However, ensuring that these communities have equitable access to the benefits of this change is paramount. This necessitates the development of strategic plans and support mechanisms that put economic considerations in conversation with environmental health, ensuring that no group is left behind in the shift towards cleaner transportation.

In essence, the transition to MDHD EVs is not merely a technological shift, but a complex socio-economic transformation. This study has highlighted the critical role of policy, technology, and equity considerations in facilitating the transition. Our research findings underscore the importance of strategically locating charging infrastructure based on detailed traffic and dwell time analyses, ensuring that both economic and environmental benefits are maximized. By integrating these insights with supportive policies and equitable practices, we can address the unique needs of different subregions within the IE. The collaborative efforts of government bodies, private sector players, and communities, particularly those most affected by vehicular emissions, are crucial for successful implementation. Aligning technological advancements with these comprehensive strategies will help to achieve the intended environmental benefits while promoting economic growth and social inclusivity.

9.2 Limitations

This report, focusing on the transition to MDHD EVs in the IE, is subject to several constraints that must be acknowledged in order to fully appreciate the implications and applicability of its conclusions.

Firstly, the study encounters data constraints. Reliance on available datasets, which may not comprehensively encapsulate all facets of MDHD EV transition, limits the depth of analysis. The dependence on secondary data sources inherently makes the study subject to the limitations of these sources, including the scope, recency, and quality of the data they provide.

Secondly, the subregional focus on the IE offers insightful findings, but also restricts the generalizability of the results. Each region possesses unique characteristics in its transition to MDHD EVs, and the IE's specific context might not fully represent the broader spectrum of challenges and opportunities inherent in such a transition.

The one-year timeframe of the study also poses limitations. This period may be insufficient to capture long-term trends and impacts fully, especially given the evolving nature of policies, infrastructure development, and market dynamics associated with MDHD EVs. Financial limitations in data acquisition present another challenge. Due to budget constraints, our access to comprehensive databases was limited. Specifically, we were unable to purchase access to certain commercial traffic and logistics datasets that could have provided more granular insights into vehicle movements and regional traffic patterns. This restriction meant relying on publicly available data, which, while useful, may lack the depth and real-time accuracy of commercial sources. Future researchers should consider allocating more funds towards data acquisition to leverage these detailed databases, which could significantly enhance the precision and scope of the analysis.

In terms of big data analysis, the selection of variables was confined to those available and accessible, with the research possibly omitting relevant variables that could offer a more nuanced understanding of the MDHD EV transition process. For instance, for the dwelling data, we had to request a tailored study from the Streetlight Data support team to have the data available for the subregions. Access to detailed data from regional governmental bodies proved challenging, limiting insights into their strategies and efforts in advancing the MDHD EV transition.

The interview process encountered several hurdles, including difficulties in identifying and engaging with suitable interviewees and potential selection bias. To mitigate these challenges, we expanded our outreach efforts by utilizing professional networks and industry associations to identify potential interviewees. Additionally, we implemented a rigorous selection process to ensure a diverse range of perspectives. Despite these efforts, engaging with the private sector remained challenging due to difficulties in establishing contacts and navigating confidentiality concerns.

Lastly, the diversity and representation in the interviews might not have encompassed the full spectrum of stakeholders involved in the MDHD EV transition, since we only interviewed 16 people. This limitation could impact the comprehensiveness and diversity of perspectives and experiences captured, potentially leading to an incomplete portrayal of the transition's challenges and opportunities.

9.3 Future Work

Future research in the field of MDHDV electrification within the IE can expand both horizontally and vertically, offering opportunities for comprehensive exploration and development. Horizontally, research efforts can focus on the incorporation of additional variables to enhance the depth and accuracy of analyses. These variables may encompass meteorological conditions, traffic flow dynamics, and infrastructural attributes. Such extensions would yield insights into the influence of environmental variables and traffic congestion on the process of MDHDV electrification. A deeper look into policy systems, including federal, state, and regional rules, can reveal a detailed picture of both the incentives and challenges involved in electrifying MDHDVs.

The vertical expansion of research in this domain can manifest through the development of advanced models and predictive systems. Specifically, the establishment of a comprehensive opportunity charging model can represent a pivotal vertical progression. This model would assimilate an array of factors, including vehicle routes, dwell times, and energy demand fluctuations to optimize the strategic placement and operation of opportunity charging stations along MDHDV routes. Moreover, a vertical approach can encompass the development of predictive models that forecast the demand and supply dynamics of electric infrastructure requisite for facilitating the transition to MDHDV electrification. These prognostic models can guide long-term planning and resource allocation, ensuring that the requisite infrastructure is deployed in a timely and efficient manner. This vertical expansion can be characterized by the exploration of sustainable energy solutions that mitigate greenhouse gas emissions. Finally, the application of advanced data analytics techniques, notably machine learning and artificial intelligence, can serve as the bedrock for vertical expansion. These sophisticated analytic methodologies can substantially augment the predictive capabilities of MDHDV electrification models, rendering them more precise and adaptive. In summation, the future of research in MDHDV electrification within the IE includes avenues for both horizontal and vertical development. By assimilating additional variables, dissecting policy and economic systems, and venturing into opportunity charging and predictive modeling, researchers can contribute to a more comprehensive understanding of the intricacies and possibilities inherent in the transition towards sustainable transportation. These strides possess the potential to sculpt the trajectory of MDHDV electrification, fostering a more environmentally responsible and operationally efficient transportation sector.

The future of MDHDV electrification research is rich with potential. By embracing both horizontal and vertical expansions, researchers can contribute significantly to the evolution of sustainable transportation. Further research will not only enhance understanding of the transition dynamics but also play a crucial role in shaping policies, technologies, and practices that support a sustainable, equitable, and efficient shift to electric MDHDVs. Continued collaboration among various stakeholders—government bodies, private sector entities, academia, and communities—will be essential in realizing the full potential of this transition.

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