

**A STRATEGIC FRAMEWORK FOR OPTIMIZING CHARGING
INFRASTRUCTURE FOR PASSENGER ELECTRIC VEHICLES AND
MEDIUM- TO HEAVY-DUTY ELECTRIC TRUCKS ACROSS PROVINCE
OF ONTARIO**

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A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTERS OF APPLIED SCIENCE

GRADUATE PROGRAM IN CIVIL ENGINEERING
YORK UNIVERSITY
TORONTO, ONTARIO

DECEMBER 2024

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Abstract

Addressing climate change and reducing greenhouse gas (GHG) emissions is driving a global shift towards electric vehicles (EVs). Canada, with its commitment to achieving net-zero GHG emissions by 2050, places high priority on accelerating EV adoption and establishing a robust EV charging infrastructure. This study proposes a comprehensive framework to optimize EV charging station deployment across Ontario, with each chapter divided into two sections: one focusing on light-duty passenger EVs within Toronto’s urban landscape and the other on medium- and heavy-duty trucks along the Highway 401-A20 corridor, spanning from Rivière-du-Loup, Quebec, to Windsor, Ontario.

Using empirical data on EV ownership, existing charging infrastructure, and travel patterns, this study develops an optimization model for passenger electric vehicles within Toronto’s wards. The model identifies the optimal number and types of chargers needed to minimize installation costs while meeting the energy demands of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). By considering factors such as charging rates, charger availability, costs, and commuting distances, it evaluates drivers’ charging behaviors for work and leisure trips and determines the required charger quantities accordingly. Additionally, the model incorporates home charging availability and the ratio of garage orphans—those without home charging options. This adaptable methodology offers valuable insights for urban planning and policy development in areas with similar needs.

Focusing on medium- and heavy-duty electric vehicles (MHDEVs), this study addresses the unique challenges of optimizing charging and route planning along the Highway 401-A20 corridor, from Rivière-du-Loup to Windsor. A key barrier to electric truck adoption lies in balancing limited range with delivery timelines while adhering to Canada’s on-duty regulations mandating driver rest periods. The study presents a robust framework that

integrates essential factors—including initial state of charge, battery consumption rates, charging station availability, and rest stop requirements—to minimize travel time and identify optimal locations for combined charging and resting facilities along this critical corridor.

Given the increasing rate of EV adoption across various vehicle classes, deploying new chargers is crucial to meet future demand. This study contributes to more effective station deployment by addressing the distinct needs of both urban and rural areas while accommodating the varying properties of different vehicle types. The developed framework provides a foundation for strategic infrastructure planning to support EV expansion in Ontario and offers a scalable approach for broader applications.

Keywords: Zero Emissions, Greenhouse Gas Reduction, Net-Zero Scenario, EV Charging Infrastructure, Truck Plazas, Rest Locations, Level 2 Chargers, DC Fast Chargers, EV Ownership, Medium-to-Heavy-Duty Electric Trucks, Long-Haul Freight Electrification, On-Duty Work Regulations, Sustainable Transportation, Urban Travel Patterns, Public Charging Access, Garage Orphans, Charging-Resting Schedule Optimization.

Acknowledgements

Beginning my master's degree at York University in Canada would not have been possible without the unwavering support and belief of a remarkable individual. To my supervisor, Mehdi Nourinejad, thank you for granting me this invaluable opportunity to join your research group and pursue my aspirations in transportation studies. Your guidance has been a beacon through all challenges, allowing me to grow and achieve in this new world I had always dreamed of. Thousands of miles away from home, family, and friends, you have been much more than a supervisor—you have been a constant source of encouragement and strength. Thank you, Mehdi, for changing my life and giving me this chance; I am deeply grateful.

I am profoundly thankful to my family—my mother, father, sister and grandmother—who, despite the great distance, have remained my backbone, offering unwavering love and support. Even across continents, their presence and encouragement have been with me every step of the way.

I also wish to express my heartfelt thanks to my partner and his family, who have given new meaning to the word "family". Their love and support have shown me that family is about having people who stand by you in tough times and celebrate your joys, even without a bond by blood.

Finally, I extend my gratitude to my colleagues at the Ministry of Transportation of Ontario, especially my manager, Mike Deruyter. Mike, thank you for believing in me and welcoming me to the team, making my transition from academia to industry smoother, and helping me take those first steps into a new world. Your confidence in me has inspired self-belief and fostered my growth.

Thank you all for your invaluable support. I am truly grateful for each of you.

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Abbreviations

BEV	Battery Electric Vehicles
BET	Battery Electric Technology
CAD	Canadian Dollar
CCS	Combined Charging System
CFC	Chlorofluorocarbon
CDLs	Call Detail Records
CNG	Compressed Natural Gas
COP	Conference of the Parties
COP21	UN Climate Change Conference
DA	Dissemination Area
DC	Direct Current
DCFC	Direct Current Fast Charger
ERS	Electric Road System
EPA	Environmental Protection Agency
EU	European Union
EV	Electric Vehicles
EVCS	Electric Vehicle Charging Stations
EVRP	Electric Vehicle Routing Problem
FCLM	Flow Capturing Location Model
FCEVs	Fuel Cell Electric Vehicles
FGW	Gross Vehicle Weight Rating
FHWA	Federal Highway Administration
FRLM	Flow Refueling Location Model

FSA	Forward Sortation Area
GB	Guobiao Standards
GHG	Greenhouse Gas
GVWR	Gross Vehicle Weight Rating
HDEVs	Heavy Duty Electric Vehicles
HEVs	Hybrid Electric Vehicles
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
ICE	Internal Combustion Engine
IEC-62196	International Electrotechnical Commission
iMHZEV	Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles
LNG	Liquefied Natural Gas
MCLM	Maximum Covering Location Model
MDEVs	Medium Duty Electric Vehicles
MHDEVs	Medium- and Heavy-Duty Electric Vehicles
MTO	Ontario Ministry of Transportation
NDCs	Nationally Determined Contributions
NRCan	Natural Resources Canada
OEMs	Original Equipment Manufacturers
PHEVs	Plug-in Hybrid Electric Vehicles
RNG	Renewable Natural Gas
SAE	Society of Automotive Engineers
SCLM	Set Covering Location Model
SOC	State of Charge
SOF	State of Fatigue
SPP	Shortest Path Problem

SUVs	Sport Utility Vehicles
TTS	Transportation Tomorrow Survey
UNFCCC	UN Framework Convention on Climate Change
USD	United States Dollar
VRP	Vehicle Routing Problem
ZEV	Zero-Emission Vehicle
ZEVIP	Zero Emission Vehicle Infrastructure Program

Chapter 1

Introduction

This chapter begins by outlining the motivation for the research, followed by a detailed discussion of the research goals, objectives, and scope. Additionally, a brief overview of the thesis structure is provided to offer a clear understanding of the topics covered in subsequent chapters.

1.1 Motivation

The urgent need to address climate change is emphasized by the rising levels of greenhouse gas (GHG) emissions, with the transportation sector as a major global contributor. To tackle these emissions, countries are adopting various strategies, including the Paris Agreement, emphasizing the importance of sustainable practices with the central goal of achieving Net Zero Emissions by 2050. A key component of this global initiative is the shift from traditional internal combustion engine (ICE) vehicles to electric vehicles, driven by supportive government policies and incentives across the globe.

The transportation sector is a major source of GHG emissions in Canada, with light-duty passenger vehicles and medium to heavy-duty trucks as key contributors. To address this challenge, the Canadian government has taken decisive action by setting ambitious national targets, such as achieving 100% Zero-Emission Vehicle (ZEV) sales by 2035. To facilitate this transition, the government has introduced financial incentives for ZEV purchases and made significant investments in the EV manufacturing sector and charging infrastructure,

promoting widespread adoption of EVs and reducing the transportation sector’s carbon footprint.

The rapid increase in EV adoption is driving a significant rise in Electric Vehicle Charging Stations (EVCSs) demand. There are currently over 9,000 charging stations and 22,000 charging ports in Canada. However, projections indicate that by 2050, the number of public charging stations required will be approximately 80 to 100 times larger, emphasizing the extensive infrastructure development needed to accommodate the anticipated growth in EV adoption [19].

The widespread adoption of EVs faces several challenges, including high purchase costs and concerns regarding range anxiety, both of which are common among potential users. To overcome these obstacles, a well-structured and adequately funded charging network is required to accommodate the growing number of EVs on the road. Strategically locating charging stations enhances accessibility and reliability, fostering greater consumer confidence in EVs as a sustainable transportation option.

The deployment of new charging stations requires a comprehensive assessment of both vehicle-specific characteristics and the attributes of deployment locations. Key factors to consider include vehicle type (light, medium, or heavy-duty), battery properties, energy consumption rates, and usage patterns in diverse weather. Deployment locations must be evaluated based on urban or rural settings, along with considerations of topographical features, travel range requirements, and traffic conditions. Furthermore, the purpose of trips in urban environments adds complexity to the deployment strategy. Consequently, deployment strategies can be divided into two primary categories: those designed for passenger vehicles in urban settings and those tailored for MHDEVs on provincial or cross-country routes, ensuring the efficient deployment of chargers suitable for various environments.

1.2 Research Objectives

Modeling Work: The primary objective of this research is to develop a comprehensive framework for optimizing the number and strategic placement of charging stations to support electric passenger vehicles and medium-to-heavy-duty electric trucks. This framework addresses the diverse requirements of these vehicle categories by integrating data-driven modeling approaches tailored to urban and long-haul transportation needs.

The study aims to improve the adaptability of charging networks by addressing infrastructure planning gaps and considering the dynamic nature of urban travel patterns for passenger EVs. The model categorizes trips into work and leisure purposes, leveraging data on EV population, average travel distances, and battery capacities. It incorporates factors such as the "garage orphan" ratio—representing users without access to home charging—and distinguishes between two charger types: Level 2 chargers, suited for work-related trips with longer charging times, and DC fast chargers, designed for leisure trips requiring quicker recharging. The objective function aims to minimize installation costs while satisfying energy demands by considering existed chargers and required new chargers. Operational factors, including charger availability rates and operational hours, are also considered to ensure efficient deployment.

Long-haul trips necessitate in-transit charging due to the infeasibility of overnight charging. This study introduces a charging-resting schedule framework within the MHDEVs section to optimize trip planning while complying with Canadian government regulations mandating an 8-hour rest period after 14 hours of on-duty work. The model incorporates variables such as initial battery state of charge, rest locations, available charging stations, battery consumption rates, average vehicle speeds, and travel distances. It also introduces a state of fatigue parameter to monitor driver tiredness and ensure compliance with regulatory requirements. By minimizing total delivery time and addressing range anxiety, the framework supports the

efficient and sustainable operation of electric freight vehicles.

Finding Data: A diverse range of data sources was employed in this study to support the analysis and modeling of EV charging infrastructure for passenger vehicles and medium-to heavy-duty trucks.

For passenger EVs, the spatial boundaries of Toronto’s 25 wards were extracted as a CSV file from the City of Toronto’s open data portal and converted into GeoJSON format, enabling integration with mapping tools including Mapbox for detailed spatial analysis and visualization. Trip data was sourced from the 2016 Transportation Tomorrow Survey (TTS), focusing on trips categorized for market/shop and work purposes, ensuring relevance to the study objectives. EV ownership data, obtained from the Ontario Ministry of Transportation (MTO), was initially categorized by Forward Sortation Areas (FSAs)—the first three characters of postal codes—and converted to align with Toronto’s 25-ward system for compatibility with spatial analysis. Additionally, existing charging infrastructure data was sourced from the Natural Resources Canada (NRCan) 2023 database, providing detailed information on station locations, the number of charging ports, and connector types, assessing the current state of infrastructure. The medium-to-heavy-duty truck section incorporates data on charging station locations and truck rest stops acquired from MTO. This dataset, comprising latitude and longitude coordinates along with station names, supports a spatial analysis of facilities situated along key freight corridors.

Model Applications: This study applied the EV charging infrastructure framework to Toronto’s 25 wards, determining the optimal number and location of new chargers based on EV users’ energy demand and the energy supply available within each ward. The model accounts for existing charging infrastructure and identifies the most efficient distribution of Level 2 and DC fast chargers to meet EVs energy demand. While the analysis focuses on Toronto, the mathematical framework is versatile and can be applied to other jurisdictions seeking to optimize their EV charging infrastructure needs. The 25-ward geographic system

was chosen for its alignment with the availability of EV trip distribution data from the Transportation Tomorrow Survey (TTS) at the ward level. This scale of analysis was deemed practical, as finer geographic divisions, such as FSAs or Dissemination Areas (DAs), were unnecessary for the study’s scope.

For medium-to-heavy-duty electric trucks, the model was applied to the Highway 401-A20 corridor, a critical transportation route connecting Ontario and Quebec. This model highlights the necessity of deploying charging infrastructure tailored to the operational requirements of these vehicles, considering factors such as battery capacity, travel distances, and resting schedules. The framework also identifies specific rest locations suitable for the installation of new charging stations. Beyond this corridor, the model can be adapted to other provincial or international highways, supporting the transition of electric fleets and promoting sustainable transportation networks.

1.3 Scope & Thesis Organization

As transitioning to sustainable transportation requires adopting both passenger electric vehicles and medium to heavy-duty electric trucks, this study is structured into two sections dedicated to each vehicle type in every chapter. Each section addresses the challenges, solutions, and infrastructure requirements unique to these vehicle categories, providing a comprehensive analysis. Further details will be explained subsequently.

Chapter 1: Introduction – This chapter addresses the global increase in greenhouse gas emissions and the subsequent need for a shift towards EVs in both passenger and medium- to heavy-duty vehicle sectors. This study underscores the need for expanded charging infrastructure to facilitate the transition to electric vehicles, with a particular focus on identifying optimal charging station locations in Ontario. Moreover, vehicle-specific characteristics alongside the geographical context of urban and rural settings are considered

to ensure effective and strategic deployment.

Chapter 2: Literature Review – This chapter provides an overview of EVs, focusing on both passenger and medium- and heavy-duty electric vehicles. It begins by discussing GHG emission statistics and ZEV strategies globally, followed by the history and evolution of EVs, different vehicle types, their characteristics, charging infrastructure, and vehicle classifications based on Gross Vehicle Weight Rating (GVWR). For passenger vehicles, current and projected market shares, charging infrastructure needs, and global incentives are examined, along with the identification of research gaps. The MHDV section explores available zero-emission technologies, market dynamics, relevant incentives, and on-duty regulations for commercial vehicles in Canada, concluding with a discussion of research gaps in this area.

Chapter 3: Study Data – This chapter describes the research design, data collection methods, and model development, divided into two subsections. The first section discusses data for optimizing passenger EV charging infrastructure, including information from Toronto’s 25 wards from the City of Toronto database [117], EV charger locations from Natural Resources Canada [108], EV ownership data by FSA from MTO [24], and electric vehicle trip distribution data from the TTS data [47]. The second section focuses on MHDEVs, detailing the Highway 401-A20 corridor as the study area and discussing data on charging and resting locations along the route, obtained from the MTO’s private database.

Chapter 4: Modeling and Analysis – This chapter outlines the mathematical modeling and optimization framework for deploying charging stations, focusing on minimizing costs by leveraging the existing network and identifying additional infrastructure needs for passenger EVs in Toronto. It also examines the charging requirements for medium- and heavy-duty vehicles along the Highway 401-A20 corridor, considering charging and resting regulations to optimize trip planning and reduce travel time.

Chapter 5: Results and Discussion – This chapter presents the findings of the study, including the optimal charging station locations and deployment costs for passenger vehicles

in Toronto’s wards, as well as the outcomes for MHDEVs along the Highway 401-A20 corridor. It evaluates the impact of the proposed charging and resting schedules on travel time and discusses the broader implications for EV infrastructure planning.

Chapter 6: Conclusions and Recommendations – This chapter provides a summary of the key conclusions drawn from the study, highlighting its contributions to EV infrastructure planning. It also discusses the limitations encountered during the research and offers potential directions for future work to further advance the deployment and optimization of electric vehicle charging networks.

Chapter 2

Literature Review

This chapter begins with a review of global GHG emissions data, highlighting key strategies and scenarios aimed at mitigating the rising trend of these emissions. The discussion then transitions to GHG emissions statistics specific to Canada. The subsequent sections assess EVs and their associated charger types while examining current EV statistics and charging infrastructure in Canada, with a particular focus on Ontario, to provide insights into the existing supply and demand dynamics. The chapter also includes an analysis of initiatives and incentives aimed at providing financial support and promoting the accelerated adoption of EVs. The chapter concludes with a comprehensive review of previous studies, highlighting research gaps and examining the algorithms and parameters used to determine the optimal locations, types, and quantities of charging stations for both passenger vehicles and commercial electric trucks.

2.1 GHG Emissions and Zero-emission strategies

Climate change poses a critical global environmental challenge, driven by the growing concentration of greenhouse gases (GHGs) in the atmosphere. Human activities, including fossil fuel consumption, transportation, and agriculture, are the primary contributors, with significant impacts on the environment, human health, and the economy.

Between 2005 and 2020, global GHG emissions increased by 18.2%. China, the United States, and India emerged as the countries with the highest emissions during this period.

China contributed 28.1% of global GHG emissions in 2020, reflecting an increase of 78.2% since 2005. The United States followed as the second-largest emitter with 11.9%, and India ranked third at 6.9% of global GHG emissions in the same year. Canada ranked 11th, made up 1.5% of global GHG emissions in 2020 [55].

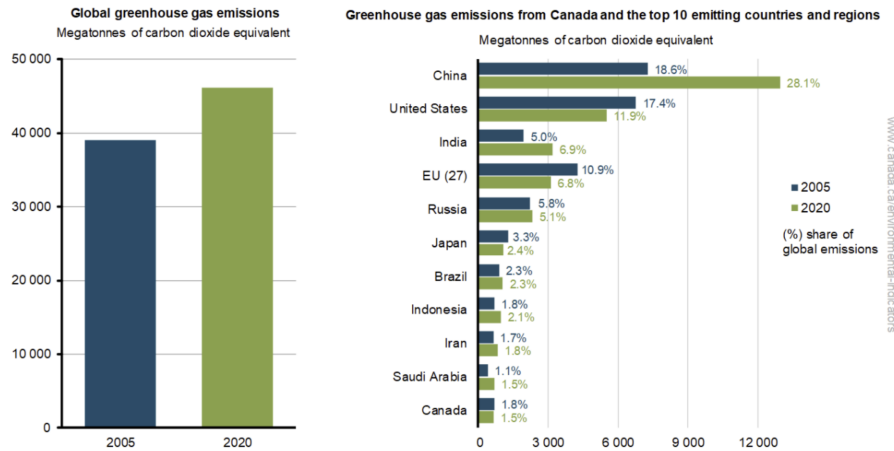


Figure 2.1: Global, Canadian, and top 10 emitting countries and regions: greenhouse gas emissions for 2005 and 2020

To address global climate change, countries endeavor to adopt international agreements. Among these, the most important are listed below:

Montreal Protocol (1987): Initially aimed at protecting the ozone layer, this protocol became a model for environmental diplomacy. It required countries worldwide to phase out substances like chlorofluorocarbons (CFCs) that deplete the ozone layer[100].

UN Framework Convention on Climate Change (UNFCCC) (1992): This landmark treaty established the framework for global action on climate change. It created the Conference of the Parties (COP) to facilitate international negotiations on reducing greenhouse gas emissions and stabilizing their atmospheric concentration. Subsequent agreements, such as the Kyoto Protocol and the Paris Agreement, emerged from this treaty [100].

Kyoto Protocol (2005): Adopted in 1997 and effective from 2005 to 2020, the Kyoto Protocol was the first legally binding treaty requiring developed countries to cut emissions

by an average of 5% below 1990 levels. It also introduced mechanisms for monitoring and reporting emissions reductions. Notably, it did not impose binding targets on developing nations[100].

Paris Agreement (2015): The Paris Agreement, considered the most significant global climate accord, was adopted by 196 parties, including Canada, at the UN Climate Change Conference (COP21). The agreement aims to limit global warming to below 2°C above pre-industrial levels, with efforts to restrict it to 1.5°C. It requires participating countries to set voluntary emissions reduction targets, known as Nationally Determined Contributions (NDCs). Additionally, the agreement emphasizes achieving global net-zero emissions in the second half of the 21st century to promote climate neutrality [100].

To keep global warming within the 1.5°C threshold, CO₂ emissions must reach net zero between 2050 and 2060. The ability to maintain the temperature increase within this limit, largely depends on how quickly major emitters can reduce their emissions. However, it is not necessary for all countries to achieve net-zero emissions simultaneously. Additionally, this strategy must specify whether it targets only CO₂ or also includes other greenhouse gases, such as methane and fluorinated gases, which have a significant warming potential. Therefore, it is essential for countries to clearly define whether their net-zero targets are limited to CO₂ or encompass all greenhouse gases, to facilitate effective climate action planning and mitigation strategies [92].

Canada has committed to several strategic initiatives since 2005 to achieve its zero-emission goals, as shown in figure 2.2 [54]. Initially targeting a 30% reduction below 2005 emissions, Canada is now pursuing the 2030 Emissions Reduction Plan, which takes a sector-specific approach to achieve a 40% reduction in emissions below 2005 levels by 2030. The plan also includes an interim goal of reducing emissions by 20% below 2005 levels by 2026, with the ultimate objective of achieving net-zero emissions by 2050 [33].

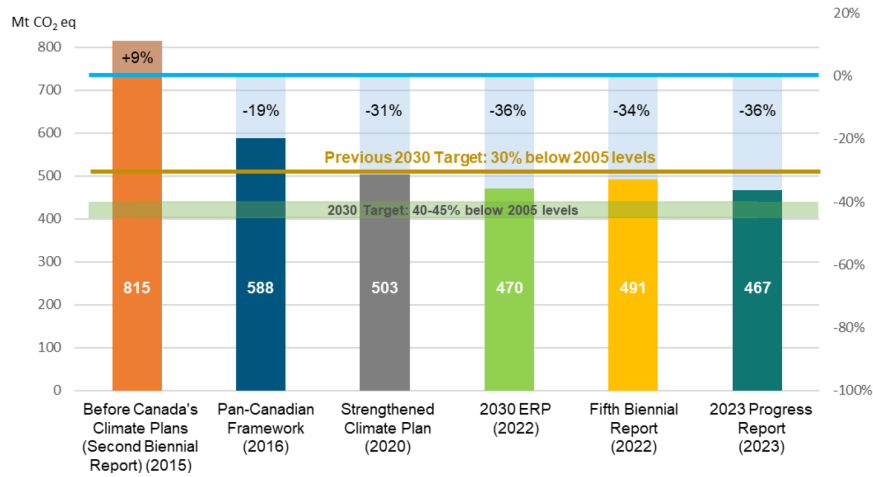


Figure 2.2: Progression of Canada's projected emissions in 2030 (Mt CO₂ eq)

The impact of different economic sectors on GHG emissions is vital to effectively mitigate this global challenge. In Canada, the oil and gas sector, along with the transportation sector, were the principal contributors, accounting for 28% and 22% of the total emissions, respectively in 2021. Moreover, between 2020 and 2021, GHG emissions in the oil and gas, transportation, heavy industry, and "waste and others" sectors increased by 2% to 5% depicted in figure 2.3. Conversely, emissions from the buildings, electricity, and agriculture sectors experienced reductions of 2% to 4% [55].

The transportation sector is the second-largest source of greenhouse gas emissions in Canada and globally, highlighting the urgent need for sustainable transportation solutions. Between 1990 and 2021, GHG emissions from the transportation sector in Canada increased by 27%, primarily due to the rising number of vehicles on the road and changes in vehicle types, as shown in Figure 2.4. During this period, total emissions from passenger transport grew by 8%, despite a 45% decrease in emissions from cars. However, emissions from light-duty trucks—including vans, sport utility vehicle (SUVs), and trucks—doubled, offsetting the decline from passenger cars. Emissions from freight transport also saw a significant increase of 62%, with heavy-duty freight truck emissions almost doubling, and emissions from other

freight modes rising by 13%. The largest annual decrease in emissions occurred from 2019 to 2020, driven primarily by the COVID-19 pandemic, which resulted in fewer kilometers driven and a reduction in air traffic [55].

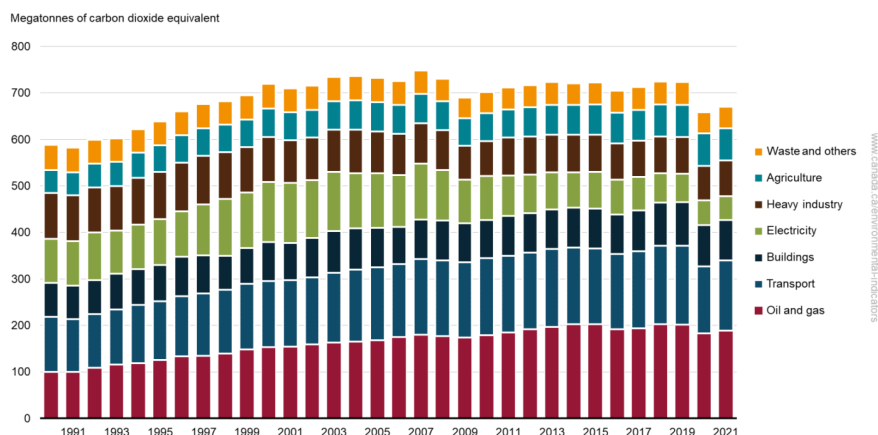


Figure 2.3: Greenhouse gas emissions by economic sector, Canada, 1990 to 2021

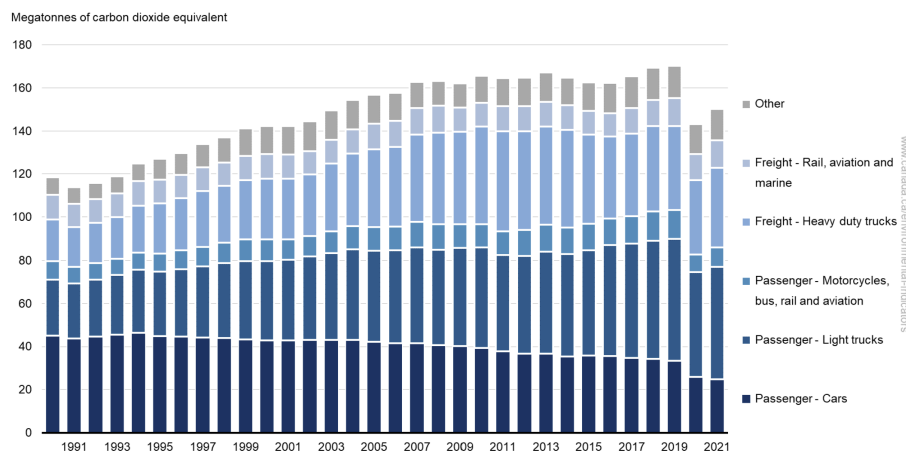


Figure 2.4: Transport sector greenhouse gas emissions, Canada, 1990 to 2021

2.2 Electric Vehicles

This section provides an overview of the history of electric vehicles, discusses the different types of electric vehicles, examines the types of charging stations and connector ports, and

outlines the classification of vehicles given their GVWR.

2.2.1 Electric Vehicle History

Electric vehicles were first introduced in the 1830s by Robert Anderson and gained considerable traction in the early 1900s, competing with gasoline and steam-powered vehicles, especially in urban areas like New York and Chicago. Their quiet operation, efficient performance, and zero emissions made them particularly popular in densely populated cities, where low speeds and shorter travel distances suited their limited battery capacity. However, their high cost and restricted range compared to gasoline-powered vehicles posed significant challenges to widespread adoption [134, 127, 105].

Despite their initial success, the market share of EVs began to decline in the 1920s due to technological advancements in gasoline vehicles, such as the introduction of electric starters and the expansion of refueling infrastructure. Gasoline-powered cars offered greater range, speed, and convenience, further compounded by the lack of a charging network for EVs. These factors contributed to the decline of EVs during this period [128, 105].

Interest in EVs was renewed in the 1990s, driven by environmental legislation such as the 1990 Clean Air Act Amendment and the 1992 Energy Policy Act. Automakers began developing modern EV models, with General Motors launching the EV1. The momentum continued in 2006 when Tesla Motors announced an electric sports car capable of traveling over 200 miles on a single charge, sparking increased investments from other automakers. By 2010, models like the Chevy Volt and Nissan LEAF entered the U.S. market, offering hybrid and fully electric options [101].

2.2.2 Electric Vehicle Types

Electric vehicles have evolved over time, leading to the development of different types designed to reduce emissions and improve energy efficiency. The primary types of electric vehicles include Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles, Hybrid Electric Vehicles (HEVs), and Fuel Cell Electric Vehicles (FCEVs), each utilizing a different combination of electric and conventional power sources, as illustrated in Figure 2.5.

Hybrid Electric Vehicles: HEVs use a combination of a gasoline engine and an electric motor. The electric motor is powered by a small battery that is recharged through regenerative braking and the engine, without requiring an external power source. The gasoline engine acts as the main power source, while the electric motor provides additional support during acceleration, enhancing overall fuel efficiency [90].

Plug-in Hybrid Electric Vehicles: PHEVs integrate both an internal combustion engine and an electric motor, with the added capability of recharging from an external power source. Unlike HEVs, PHEVs have larger batteries, enabling them to run solely on electricity for a specified range before transitioning to the gasoline engine for extended trips. This flexibility makes PHEVs ideal for short, emission-free commutes as well as longer journeys powered by gasoline [90].

Battery Electric Vehicles: BEVs rely entirely on electricity for propulsion. They are powered by a large battery pack, charged from the grid through external charging stations. BEVs have no internal combustion engine and, therefore, produce zero emissions during operation. These vehicles are designed for maximum energy efficiency and are increasingly popular due to advancements in battery technology, which have extended their driving range[90].

Fuel Cell Electric Vehicles: FCEVs generate electricity through a chemical reaction between hydrogen and oxygen within a fuel cell stack. This process produces electricity

to power an electric motor, with water as the only byproduct, making it a clean energy solution. Like BEVs, FCEVs are electrically powered; however, they differ in how they generate electricity. Rather than depending on stored battery power, FCEVs utilize hydrogen fuel, which allows for longer driving ranges and faster refueling times compared to BEVs. This makes FCEVs particularly well-suited for applications requiring extended range [90].

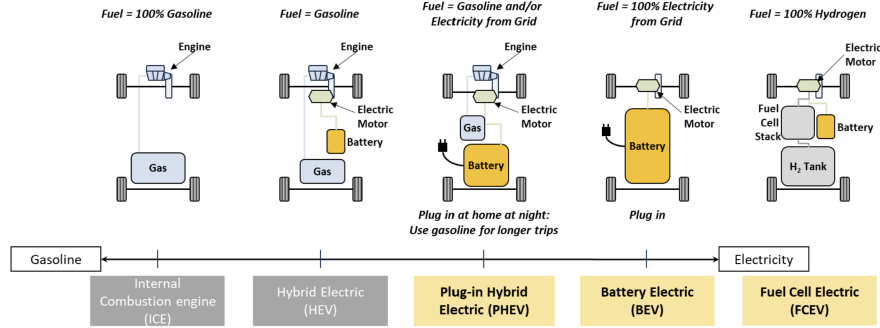


Figure 2.5: Power sources and propulsion systems comparison of ICE, HEVs, PHEVs, BEVs, FCEVs [1]

2.2.3 Charging Infrastructure Types

The charging process is a critical component in the adoption of electric vehicles. Facilitating widespread EV uptake requires charging solutions that are both fast and convenient, ensuring a seamless user experience. Moreover, standardizing chargers across regions and countries is essential to ensure compatibility between different EV models and charging stations, supporting long-distance and cross-border travel.

In North America, the Society of Automotive Engineers (SAE) standard, established in 1996, classifies EV charging into three levels based on charging method (AC/DC), voltage, current, and power output [21]. This standard, widely used in the United States and Japan, provides a consistent framework for EV connectivity and will be discussed in greater detail further in this section. In China, the Guobiao Standards (GB) standard is used, while Europe follows the International Electro-technical Commission (IEC-62196) standard. The

primary distinction between these standards is that while the North American and Chinese standards classify charging modes by power type, the European standard categorizes them based on charging power levels [126, 7], defining voltage compatibility, and charging speed of connectors, to ensure efficient and reliable charging across various markets.

Table 2.1: Charging levels of EV according to SAE J1772 standard [7]

Charging Levels	Level 1	Level 2	Level 3
Phase	AC (1 Phase)	AC (1 / 3 Phase)	DC
Voltage (V)	120 V	230-400 V	400 V-Higher
Current (A)	10-16	16, 32 or 63	63 Up to 400
Power (kW)	1.4-1.9	3.7-22	44-Higher
Installation	Domestic Location	Domestic/Public Location	Public Location

Level 1 Charging: Level 1 charging uses single-phase AC power at 120 V, delivering a current between 10A to 16A. The power output of Level 1 charging typically ranges from 1.4 to 1.9 kW, making it the slowest form of EV charging. This type of charger is primarily used in residential settings and is ideal for overnight charging of light-duty electric vehicles. Level 1 charging is suitable for smaller EVs with limited battery capacities. It takes 40 to 50 hours to charge a BEV from empty to 80%, while PHEVs take 5 to 6 hours. with an approximately 8 km range per hour of charging, this charging option is less convenient [126, 7, 61].

Level 2 Charging: Level 2 chargers provide a faster charging option, using single-phase or three-phase AC power with voltages between 230 and 400 V. Depending on the current (16, 32, or 63 A), these chargers deliver power ranging from 3.7 to 22 kW. They are used in domestic and public settings, making them suitable for overnight or daytime charging of light and medium-duty electric vehicles. Common installation locations include residential homes, public parking areas, and workplaces. Level 2 chargers can charge an empty BEV to 80% in 4-10 hours, a PHEV in 1-2 hours, and take more than 10 hours to fully charge a medium to heavy-duty electric truck battery. Compared to Level 1 chargers, this charger

type is faster, providing approximately 35 km of range per hour of charging [7, 118, 53, 61].

Level 3 Charging (DC Fast Charging): Level 3 charging, also referred to as DC fast charging, operates on DC and supports voltages of 400 V or higher. These chargers offer significantly faster charging speeds, with currents ranging from 63 to 400 A and power outputs starting at 44 kW. Designed for public locations, Level 3 chargers are well-suited for quickly recharging heavy-duty electric trucks and buses, typically achieving a full charge within 45 minutes to 2 hours at 250 kW [126, 7, 53].

The development of charging infrastructure technologies is progressing rapidly, with several companies pioneering high-powered charging solutions to meet the growing demand. Tritium is developing a 350 kW charger designed to function effectively in extreme temperatures, ranging from -35°C to $+50^{\circ}\text{C}$. In Ontario, Phoenix Contact is working on a 500 kW charging system, while BMW Group and ChargePoint are preparing to deploy infrastructure with power capacities exceeding 400 kW. Furthermore, Tesla has announced the establishment of a network of Megachargers with power capacities ranging from 750 kW to 1 MW, capable of delivering up to 640 kilometers of range within 30 minutes of charging. These Megachargers represent a significant advancement over Tesla's current V3 Superchargers, limited to 250 kW [139, 40, 7].

2.2.4 Charging Infrastructure Connector Types

The connector type is another important factor of EV infrastructure, complementing the charging infrastructure types discussed in the previous subsection. Ensuring compatibility between a vehicle's charging port and the charger outlet is critical, as different EV models, depending on the manufacturer, use distinct connector types. These connectors vary by vehicle model, country of origin, and charging level, all of which will be examined in detail:

Table 2.2: Electric vehicle connectors by standards

Connector Type	AC/DC	Max Output Power	Charging Time	Region/Area
SAE J1772				
Type 1	AC	1.92 - 19.2 kW	Level 1-2 (Slow)	U.S., Canada, Japan
CCS Type 1	DC	360 kW	Level 3 (Fast)	U.S., Canada, South Korea
Mennekes				
Type 2	AC	7.6 - 22 kW	Level 2 (Slow)	EU, UK, MEA, Australia
CCS				
Type 2	DC	360 kW	Level 3 (Fast)	EU, UK, MEA, Australia
CHAdemo				
No Type	DC	400 kW	Level 3 (Fast)	Japan (Older models)
GB/T				
Type 1	AC	7.4 kW	Level 2 (Slow)	China
Type 2	DC	237.5 kW	Level 3 (Fast)	China
Tesla				
No Type	AC/DC	250 kW	Level 2-3 (Fast)	U.S., Canada

SAE J1772: The SAE J1772 standard is divided into two primary types, each designed to meet different charging requirements. The SAE J1772 (Type 1) connector is the standard for AC charging in North America and Japan, operating at 120V to 240V. It is widely used for Level 1 and Level 2 charging in residential and workplace settings, providing compatibility with popular electric vehicles like the Nissan Leaf, Chevrolet models, Toyota, and Tesla (with an adaptor). In addition to Type 1, the SAE J1772 (Type 2), also known as the Combined Charging System (CCS), supports both AC and DC charging. This dual functionality allows for faster charging times and greater flexibility, making it a common choice for a broad range

of vehicles, including those previously mentioned [16].

CCS - Type 2: The Combined Charging System (CCS) Type 2, an enhancement of the "Mennekes" connector, incorporates two additional DC pins that enable high-speed charging capacities of up to 350 kW. This dual capability allows the same port to support both AC and DC charging, making it a versatile and efficient solution for rapid EV charging across regions including the EU, UK, MEA, and Australia[16].

Mennekes: In European markets as well as the Middle East, Africa, and Australia, the Mennekes connector serves as the standard for AC charging, operating at 230V and primarily facilitating slower charging sessions. This connector is widely applied in vehicles like the Renault Zoe, offering reliable charging solutions for residential and public charging stations[16].

CHAdemo: The CHAdemo connector is a widely used DC charging standard, capable of supporting both slow and fast charging at 400kW. It is prevalent in Japan, as well as older EV models across the U.S. and Europe, with vehicles such as the Nissan Leaf, Mitsubishi, KIA, and Tesla (with an adaptor) utilizing this connector for rapid charging[16].

GB/T: In China, the GB/T connector is the standard for both AC and DC charging. The AC version is used for slow charging, while the DC version supports fast charging, making it the dominant connector in the Chinese market[16].

Tesla: Tesla vehicles use a proprietary connector for both AC and DC charging, allowing for slow and fast charging across all markets except Europe. In Europe, Tesla conforms to regional standards by utilizing the Mennekes connector for charging compatibility[16].

2.2.5 Vehicles Type Classification

This study examines the classification of vehicles into two primary categories: passenger vehicles and medium- to heavy-duty trucks, with a focus on addressing their distinct electrifi-

cation needs. These classifications are shown in table 2.3, and will be discussed in detail in this section.

Vehicles can be classified using various criteria, such as their size, function, or weight. However, considering the GVWR is one of the primary classifications, representing the maximum allowable weight of a fully loaded vehicle, including its own weight, cargo, passengers, and fluids. To establish regulatory and operational standards, several key organizations utilize GVWR as a central metric. The Federal Highway Administration (FHWA) classifies vehicles into eight weight classes (Class 1 to 8), primarily focusing on commercial vehicles. The U.S. Census Bureau takes a broader approach, categorizing vehicles into light-duty, medium-duty, light heavy-duty, and heavy-duty segments, based on their functional roles. The Environmental Protection Agency (EPA) differentiates between light-duty vehicles (under 8,500 lbs GVWR) and heavy-duty vehicles (over 8,500 lbs GVWR), with further subdivisions to address emissions standards and vehicle types. Each of these classification systems plays a crucial role in shaping vehicle regulations, emissions control, and infrastructure planning, underscoring the importance of GVWR in these frameworks. [142].

This study considered the FHWA vehicle classification system, widely used in transportation planning and policy. This method classifies vehicles into eight classes based on their GVWR. Class 1 and Class 2 vehicles, which have a GVWR below 10,000 lbs, are categorized as light-duty vehicles, typically including passenger vehicles and small commercial vans. Classes 3 to 6, with GVWRs ranging from 10,001 lbs to 26,000 lbs, represent medium-duty vehicles such as delivery trucks and larger commercial vans. Classes 7 and 8, with GVWRs above 26,001 lbs, are categorized as heavy-duty vehicles, including large freight trucks and semi-trailers [84].

The TTC database provides limited information on light-duty vehicles, focusing primarily on passenger vehicles. As a result, the first part of the study is dedicated to passenger vehicles. The second part of the study addresses medium- and heavy-duty electric vehicles, reflecting

the greater availability of data for these vehicle types.

Table 2.3: Federal highway administration vehicle weight classification

Gross Vehicle Weight Rating (lbs)	Vehicle Class	GVWR Category
< 6,000	Class 1	Light Duty
6,001 – 10,000	Class 2	
10,001 – 14,000	Class 3	Medium Duty
14,001 – 16,000	Class 4	
16,001 – 19,500	Class 5	
19,501 – 26,000	Class 6	
26,001 – 33,000	Class 7	Heavy Duty
> 33,001	Class 8	

2.3 Passenger Electric Vehicles

This section reviews key information regarding passenger EVs. We begin by examining the current and projected global share of EVs, with a particular focus on Canada. Following this, we explore detailed data on the quantity of charging infrastructure, representing the supply side of the market to address charging needs in the country. We also discuss global initiatives and incentives aimed at increasing EV adoption rates. Lastly, we review existing literature to identify research gaps, particularly regarding the insufficiency of charging stations based on previous studies.

2.3.1 Current and projected EV Market share

The global market share of passenger electric vehicles has been growing rapidly as part of the broader effort to combat climate change. In 2015, light-duty vehicles contributed to nearly half of all greenhouse gas emissions, highlighting the urgent need for cleaner alternatives [107]. However, in 2018, the EV market share remained negligible, with non-electric vehicles accounting for 97.59% of the nearly 85 million cars sold globally. By 2022, the global EV stock had surged to 26 million, reflecting the accelerating adoption of electric vehicles. This momentum continued into 2023, with the share of non-electric vehicles dropping to 81% and EVs accounting 19% of global sales. This remarkable shift underscores the exponential growth of EVs, which rose from just 20,400 in 2012 to over 40 million by 2023. With strong competition and the introduction of relatively low-cost electric cars, EV sales are expected to grow by nearly 25% in 2024 compared to the previous year, reaching around 10 million units[122, 77].

In Canada, the EV market has experienced significant growth, reflecting the country's transition toward more sustainable transportation options. In 2017, EVs represented just 1% of new vehicle acquisitions, with 19,696 units sold. By 2019, this figure had nearly tripled

to 56,165 vehicles, accounting for 2.9% of the market. The upward trend continued in 2021, with 86,032 EVs registered, making up 5.3% of all vehicles sold. In the first quarter of 2022, another milestone was achieved, with 26,018 EV registrations, accounting for 7.7% of vehicle sales during that period [133]. Approximately 75% of these registrations consisted of battery BEVs, with PHEVs accounting for the remaining portion. This growth has been particularly concentrated in Quebec, British Columbia, and Ontario, which together accounted for 94% of Canada’s new EVs in 2021 [32]. By 2023, the total number of EVs on Canadian roads had reached approximately 550,000, reflecting the nation’s increasing commitment to environmentally responsible transportation [122].

Ontario, in particular, has seen steady growth in EV adoption. As of December 2023, the province had over 150,000 registered electric vehicles, including both BEVs and PHEVs. In the first two quarters of 2022, Ontario added 16,000 EVs, which accounted for 5.5% of all new vehicle registrations in the province. By the first quarter of 2023, the total number of EVs had risen to nearly 110,000, with BEVs comprising 72% and PHEVs 28%. This upward trend continued into 2024, with the total number of registered EVs nearing 160,000, including 118,000 BEVs and 42,000 PHEVs. This growth reflects Ontario’s increasing commitment to promoting sustainable transportation solutions [120].

Looking ahead, the future of electric vehicles in Canada is promising, with the Canadian government setting a mandatory target for all new light-duty vehicle sales to be zero-emission by 2035. This includes both BEVs and PHEVs, with projections estimating the sale of 2 million ZEVs and a total of 12.4 million ZEVs on the road by 2035 [5]. By 2050, it is expected that 280 million BEVs will be in use globally out of a total of 296 million vehicles [147]. Provincial governments have also set ambitious goals: Quebec aims to have 1.5 million light-duty electric vehicles by 2030 [14], and Ontario plans to achieve 5% EV penetration by 2025, 20% by 2030, and 80% by 2040. These targets highlight the strong commitment of both federal and provincial governments to supporting the transition to electric vehicles and

ensuring the necessary infrastructure is in place to meet future demand [2].

2.3.2 Current and projected EV Charging infrastructure

Charging infrastructure is an essential component in addressing the energy requirements of electric vehicles. As the adoption of EVs continues to rise, substantial investments are being made worldwide to strengthen and expand charging networks. For instance, Japan has set a goal of installing 150,000 public charging stations by 2030. In the United States, USD 1.5 million has been allocated to build charging stations along 75,000 miles of highways, ensuring extensive coverage. The European Commission has also committed EUR 1.5 billion to the development of charging infrastructure throughout the continent’s road networks [76].

In Canada, over 9,000 charging station locations and 22,000 charging ports were deployed across the country, by 2021. Since then, the number has grown, with more than 12,000 charging stations and over 30,000 charging ports available nationwide in 2024. The majority of these chargers, nearly 85%, are concentrated in the provinces of Ontario, Quebec, and British Columbia. To further support the growing demand for electric vehicles, Canada has committed to a significant investment of CAD 500 million aimed at installing 84,500 additional charging stations by the end of 2029 [60, 29].

In Ontario, there are currently more than 3,700 charging stations and 10,600 charging ports established across the province. Of these, nearly 100 charging stations and 150 charging ports are owned by the provincial government and municipalities, while approximately 800 stations and 3,400 ports are privately owned. The province’s charging infrastructure includes nearly 3,000 Level 2 and 500 DC Fast Charger locations, with 32 Level 2 chargers available for free in carpool parking areas. The installation and maintenance of these stations are managed by various network operators such as Petro-Canada, Tesla, and FLO, each of which offers different membership programs and pricing structures [61, 29].

To address the future charging infrastructure needs, projected ev charging demand should be predicted. The Federal Government’s Projections of Canada’s Public Charging Infrastructure Needs estimate that by 2025, 48,000 Level 2 and 4,300 DC fast charging stations will be required to accommodate the growing number of EVs and meet the target of 100% market share for new light-duty vehicle sales by 2035. These figures are expected to nearly triple by 2030 and increase tenfold by 2040. By 2050, over 727,000 public charging stations will be needed, with 1% of them being DC fast chargers and the rest Level 2. Additionally, each public charging station should serve 20 EVs in 2025, increasing to 43 EVs per station by 2050. To support these goals, the government has committed \$20 billion over the next 30 years to expand public charging infrastructure, with stations placed every 65 kilometers along highways, and each equipped with at least two charging ports.[21, 110].

2.3.3 Initiatives and Incentives

Many countries are increasingly adopting initiatives and incentives to accelerate the shift from ICE vehicles to ZEVs. These measures include financial incentives, tax breaks, and large-scale investments in charging infrastructure. Countries such as Sweden and France have introduced purchase incentives ranging from €1,000 to €6,000, while cities like Oslo provide free charging, and Madrid and Helsinki offer tax reductions and parking advantages for ZEV owners. These efforts are further supported by significant investments in infrastructure, with Japan aiming for 150,000 public charging stations by 2030, the U.S. allocating USD 1.5 million for highway chargers, and the European Commission committing EUR 1.5 billion to enhance charging networks [125, 76].

In line with global trends, Canada is also advancing ZEV adoption through a variety of federal and provincial initiatives supporting ZEVs and medium- to heavy-duty electric trucks. Under the iZEV policy, the federal government provides incentives to increase zero-emission

passenger vehicles, committing \$2.3 billion. Provincially, jurisdictions subsidize purchases of new passenger EVs, ranging from \$4,000 per eligible vehicle under B.C.’s CleanBC rebate to a maximum of \$7,000 in Quebec [9, 65, 65, 138, 13].

To enhance its charging infrastructure network, Canada has committed further support for the EV transition under the federal Zero Emission Vehicle Infrastructure Program (ZEVIP). Launched in 2019 with a budget of \$280 million, this program aims to deploy 33,500 electric vehicle chargers and 10 hydrogen refueling stations in public spaces, as well as in commercial and residential buildings, over a five-year period [109]. Provincial policies, such as Ontario’s EV ChargeON program by the Ministry of Transportation, aim to upgrade public infrastructure with funding of up to \$1 million per project for government and community sites [62]. Additionally, the Government of Quebec offers up to \$600 in financial assistance for the acquisition and installation of eligible home charging stations [64]. In British Columbia, incentives are provided for apartment and condo buildings, ranging from \$3,000 per parking space for residential units, to \$14,000 for the purchase and installation of eligible Level 2 networked EV chargers for workplace use [35].

Implementing regulatory and fiscal measures, Canada adopted the Greenhouse Gas Pollution Pricing Act, introducing a carbon tax that funds a \$15 billion investment over the next decade [31]. Additionally, a carbon tax rebate is being considered for residents in certain provinces [63]. Ontario has introduced the distribution of green license plates for eligible passenger vehicles and trucks with a registered gross weight under 3,000 kg, allowing them to use High Occupancy Vehicle (HOV) lanes and High Occupancy Toll (HOT) lanes with any number of occupants. These comprehensive initiatives and policies underscore Canada’s commitment to advancing EV adoption and supporting sustainable transportation.

2.3.4 Charging infrastructure optimization Problems

Given the continued growth of EV adoption, the expansion of charging infrastructure is becoming increasingly important, making the identification of optimal charging station locations essential. A key approach to addressing this challenge is through facility location problems, which are widely studied in the literature. These methods are typically divided into two categories: node-based and flow-based approaches. Flow-based methods can be further subdivided into tour-based and path-based models, depending on whether charging stations are placed along network links (path-based) or at strategic nodes (tour-based). Both node-based and flow-based methods are explored in detail, providing insight into their applications and highlighting their importance in the efficient deployment of EV charging infrastructure.

Node-based approach

The node-based approach is a facility location model that focuses on identifying the optimal locations for EV charging stations by considering specific nodes within a network, such as cities, intersections, or key demand points. The primary objective of this approach is to optimize key considerations, such as reducing transportation costs, maximizing the coverage of demand points [66, 71], and achieving load balancing across various facilities [46]. This method is effective in scenarios where demand is concentrated at discrete locations, enabling strategic placement of charging stations to serve the points' demand efficiently [103]. This approach can be further classified into three categories: the Set Covering Location Model (SCLM), the Maximum Covering Location Model (MCLM), and the p-median approach, each of which will be discussed in detail.

The Set Covering Location Model (SCLM) aims to minimize the number of facilities required while ensuring that all demand points are within a specified distance of a facility

[103]. In this model, each demand point is given equal importance, with the primary goal of achieving comprehensive coverage of all demand nodes.

Wang et al. adapted this model to develop a refueling station placement strategy using mixed-integer programming based on vehicle-routing principles to ensure the accessibility of all nodes within a transportation network [145]. Similarly, [146] applied the SCLM to maximize demand coverage for intra- and inter-city trips while minimizing costs, assuming unlimited station capacity. Vazifeh et al. applied this model to optimize mobility data across a geographical grid in Boston, aiming to minimize drivers' excess travel distances, reduce energy consumption, and improve charging station placement by utilizing Call Detail Records from one million users over four months[143]. Enhancing the SCLM with statistical machine learning (SML), Özşahin and Erdebilli proposed a methodology for optimizing EV charging station locations, ensuring full coverage within a predefined travel distance and minimizing overall network establishment costs using Denmark's Capital Region road transportation dataset [121].

The Maximum Covering Location Model (MCLM) is another node-based approach designed to place a specified number of facilities to maximize demand coverage, considering a critical distance similar to the SCLM [103]. In contrast, the MCLM allows some demand nodes to remain uncovered, making it suitable for scenarios where resources are insufficient to cover all nodes. This model is particularly useful in realistic situations where complete coverage is not feasible. Frade et al. applied the MCLM approach in a case study in Lisbon, Portugal, to determine optimal locations for slow charging stations, adjusting station size based on local demand to achieve the maximum coverage [57]. [135] proposed a model for locating charging stations based on the travel behaviors of urban residents in China, considering two distinct scenarios: parked vehicles and vehicles on long journeys. Also, the model differentiates between short-distance commuters who utilize slow charging facilities and long-distance travelers who require fast recharging outlets. Moreover, Wanger et al.

developed a decision support system for deploying new charging stations in Amsterdam using a regression model. They incorporated the Google Maps API to collect points of interest data, including schools and shopping malls, as well as existing charger locations, to maximize the utilization rate of chargers[144]. [102] used the genetic algorithm to analyze the deployment of EV charging stations by considering factors such as opening costs, distances between stations and clients, and city power grid capacity. [124] adopted a Mixed-Integer Non-Linear Programming approach to optimize the placement and sizing of fast charging stations, considering development costs, EV energy loss, grid loss, and the locations of substations and urban roads. [59] and [48] considered additional factors, including charging delays due to station congestion and road network traffic, to enhance the accuracy of their models.

The p-median model, introduced by [67], is a prevalent model in facility location problems. This model aims to determine the optimal locations for facilities from a set of candidates to minimize the total transportation cost or the weighted distance between customers and facilities, ensuring each customer is assigned to a facility. Moreover, this model can incorporate capacity constraints, where facilities have a limit on the demand they can serve. This aspect is important to consider in charging station applications, where capacity directly affects availability. [81] forecast the number of EVs at different penetration rates and project the overall charging demand by analyzing average daily mileage and energy consumption. This demand is categorized into slow, regular, and urgent charging needs. The study employs a p-median model to strategically plan fast charging stations along major roads in Beijing, considering traffic volumes and road lengths to determine the optimal locations and number of charging stations. [82] integrated the p-median model into a bi-level problem to strategically locate charging stations for taxis, optimizing both travel distance and queuing time. [8] analyzed private vehicle usage data in Rome to devise an optimal strategy for distributing charging infrastructure, estimating energy demand for

urban subareas assuming a complete transition to electric vehicles. [49] addressed multiple objectives, including cost, network operational parameters like voltage stability, reliability, power loss, and EV driver convenience metrics, using a hybrid algorithm based on Pareto dominance in Guwahati City, India. [96] developed an integrated optimization platform for estimating charging infrastructure placement at home and non-home locations in the Greater Sacramento Area and San Diego, considering infrastructure costs and dynamic electricity prices through mixed-integer linear programming. [75] aimed to maximize profit by considering installation, operational, maintenance costs, and land acquisition expenses and used the Genetic algorithm to optimize the placement and number of fast EV charging stations in Boston. [137] has proposed an improved p-median model to optimize the placement of EV charging stations, focusing on minimizing customer time costs, including travel and waiting times, while considering station capacity and demand. Dijkstra’s algorithm has been used for shortest route determination and speed classification for accurate driving times, combined with queuing theory to address service reliability. [4] introduced a model combining optimization and system dynamics to enhance EV infrastructure planning, validated with historical data at Qatar University, determining optimal sizes and installation timelines for EV chargers, incorporating solutions such as solar PV systems.

Flow-based approach

Flow-based approaches optimize the placement of EV charging stations by analyzing vehicle movement patterns within a network, concentrating on the distribution of demand along the network’s edges. This approach contrasts with node-based methods, which restrict demand to specific nodes. Utilizing traffic data, vehicle trajectories, and travel demand, this approach locates charging infrastructure to effectively address the dynamic needs of EV users [141]. The concept of deploying charging stations at either nodes or edges has led to the development of path-based and tour-based approaches, respectively. However, this study considers both

concepts under the broader category of flow-based models without distinction. Flow-based approaches include models such as the Flow Capturing Location Model (FCLM) and the Flow Refueling Location Model (FRLM).

Flow Capturing Location Model (FCLM), proposed by Hodgson in 1990, aims to optimize infrastructure placement by maximizing the number of vehicles passing through the stations [73]. [85] extended this model to account for asymmetric power consumption due to terrain, road gradients, and battery uncertainties related to age, technology, and charging duration using the Partial Sample Approximation method. The Multi-Period Multi-Path Refueling Location Model, developed by Li et al., expands public EV charging networks to support origin-destination trips. This heuristic model is based on a genetic algorithm, capturing the network’s topological structure and determining cost-effective station schemes across spatial and temporal dimensions. It has been validated with the Sioux Falls road network and a South Carolina case study [95]. Kadri et al. optimized EV fast charging station locations within a limited investment budget, considering uncertainties in recharging demand and variations in the number of EVs and available budgets each year. They used a Multi-Stage Stochastic Integer Programming approach, solved with Benders decomposition and a genetic algorithm, to maximize EV drivers’ recharging satisfaction [83].

The Flow Refueling Location Model (FRLM), introduced by Kuby and Lim in 2005, considered the range anxiety as a constraint to maximize the alternative-fuel vehicles flow [89]. He et al. considered placing DCFC stations across the U.S. to maximize long-distance trip completion using travel data. Their study addressed the fast-charge facility location problem from a network perspective, focusing on travel demands and feasible distances. The FRLM was formulated to find optimal charging sites, clustering origin and destination points into 196 locations, and solved as a mixed-integer program using a branch-and-bound algorithm [72]. Moreover, He et al. proposed a bi-level programming model to solve the EV charger deployment issue, aiming to reduce range anxiety. The upper level of the model

aims to maximize the path flows using the charging stations, while the lower level addresses the user equilibrium of route choice within the EV's driving range constraint [70]. Kinay et al. introduced a full-cover modeling framework to optimize the design of fast-charging stations for battery electric vehicles. This model ensures all origin-destination trips on a transportation network are covered with minimal en-route recharging, allowing deviations from the shortest paths [87].

2.4 Medium-to-heavy duty Electric Trucks

The global shift towards zero-emission vehicles is rapidly advancing, not only in passenger electric vehicles but also significantly in the medium- and heavy-duty vehicle sectors. In 2015, heavy-duty trucks accounted for approximately 39% of GHG emissions within the transport sector. Without intervention, carbon dioxide emissions from commercial trucks could nearly double, escalating from 4 billion metric tons in 2015 to 8 billion metric tons by 2050 [107]. Shifting from conventional ICE trucks to zero-emission electric trucks offers a prominent solution, leading to a substantial reduction in emissions by 42%-61%, and 43% lower energy consumption [91]. Beyond environmental benefits, electric trucks also provide operational advantages, including improved reliability, reduced maintenance needs, engine simplicity, and enhanced driver comfort and accessibility [126].

2.4.1 ZEV Technologies and Challenges:

The advancement of zero-emission MHDV technology relies on various innovations, including battery-electric trucks, hydrogen fuel cells, catenary systems, and advanced biofuels. Each of these technologies brings its benefits and challenges, thereby contributing to a multifaceted strategy to reduce global emissions. A detailed discussion of these technologies and their respective impacts will follow in subsequent sections.

Battery Electric Technology (BET): Battery electric trucks rely on onboard battery packs charged via plug-in systems to power electric motors and drive axles, offering a cleaner alternative to traditional diesel engines. These trucks also use regenerative braking to convert kinetic energy into electrical energy, enhancing overall efficiency [106].

The number of battery electric trucks is steadily increasing globally, with nearly 60,000 medium- and heavy-duty electric trucks sold worldwide in 2022, representing about 1.2% of total truck sales. China dominates the production and sales of electric trucks and buses, with

an estimated 52,000 electric trucks sold in 2022, accounting for 85% of the global market. In Europe, adoption has been slower, with nearly 2,000 electric trucks sold across the entire European Union during the same year[76]. However, the adoption of electric buses has been particularly notable in several European countries. In Finland, electric buses accounted for two-thirds of all bus sales, while in Norway and the Netherlands, they represented about half of all sales and nearly one-third in Denmark [76].

Battery electric trucks face several challenges, hindering widespread adoption, particularly in long-haul applications. One limitation arises from the battery’s weight, which reduces the vehicle’s payload capacity and decreases its efficiency for transporting goods over long distances. Furthermore, despite cutting-edge charging technology with maximum rates of 350 kW, charging times remain relatively long, resulting in a range of less than 500 kilometers. Additionally, electric trucks must adapt to higher voltage requirements for the upcoming MCS technology, which will require both technological improvements and standardized cross-border charging infrastructure. The recently announced Canada and United States Alternative Fuel Corridor, which aims to install EV charging stations every 80 kilometers, has the potential to address some of these issues by supporting the electrification of Class 8 trucks [106]

Cold weather conditions impose considerable constraints on battery electric trucks, as temperatures below -20°C can increase energy consumption by approximately 20% due to increased air resistance and the additional energy demand for cabin heating. However, these obstacles can be mitigated through careful logistical planning, such as keeping vehicles plugged in at depots to maintain optimal battery temperature before operation. The high cost of installing fleet-operated chargers is another barrier despite their potential to enhance charging efficiency for fleet operators. To make battery electric trucks viable for long-haul operations, public charging stations must be strategically deployed at key locations, ensuring supply can adequately meet demand [106].

Company	Region/Province	Company Details	Fleet Details	References
Home Hardware	Greater Toronto Area (GTA)	Dealer-owned and operated home improvement retailer	2 Volvo VNR electric Class 8 semi trucks, launched in September 2024 for last-mile deliveries	[97, 79]
Martin Brower	GTA and Montreal	Supply chain company	10 Volvo VNR electric trucks to serve McDonald's restaurants, 7 in GTA and 3 in Montreal	[15, 80]
Kruger Energy	Quebec (QC)	Developing and managing green and renewable power plants	2 Peterbilt 579EVs BEV Class 8 trucks operate for shuttle services between two locations, 71 km apart - Placed orders for 65 additional electric trucks from Peterbilt, Lion, and Tesla	[52, 131]
FedEx	Toronto, Montreal, Surrey	Shipping and delivery company	50 BrightDrop EVs, powered by GM's Ultium Platform, with a 400 km range for last-mile deliveries - Part of a broader plan to deploy 2,500 EVs across FedEx operations	[18, 79]
Walmart	North America	Retail corporation, operates a chain of supermarkets and grocery stores	- Walmart plans to fully electrify its entire vehicle fleet, including long-haul trucks, by 2040 - Walmart Canada has increased its reservations of Tesla electric semi-trucks to 130 vehicles - In British Columbia, Walmart deployed its first 3 electric semi-trucks at the Surrey distribution center, expected to save over 100,000 liters of fuel annually	[43, 36, 30]
Amazon	North America	North America's largest e-commerce retailer	Aims to acquire as many as 2,500 battery-powered electric trucks from Lion Electric Co. by 2025	[68]
CNTL	North America	Pickup and delivery service	Procured 50 Class 8 electric trucks from Lion Electric Co. for transporting containers from intermodal facilities to customer destinations	[39, 38]
Loblaws	Canada	Loblaws is Canada's largest food and pharmacy retailer	- Adding 10 Freightliner eCascadia trucks in Vancouver - Ordered 25 new Tesla Semis	[98, 149]

Table 2.4: Examples of electric vehicle fleet deployments by major companies in North America

Catenary Technology: Catenary trucks represent an emerging technology in electrifying medium- and heavy-duty transportation, utilizing overhead power lines to deliver electricity directly to the vehicle through deployable pantographs. This allows trucks to connect and disconnect while moving along electrified roads, enabling efficient dynamic charging. Trucks powered by catenary systems exhibit substantial energy efficiency, with utilization rates reaching up to 76% compared to traditional diesel trucks, as they can directly use electricity while in motion [106]. Although catenary trucks are still in the early stages of deployment and have yet to be tested on Canadian highways, several pilot projects have been conducted globally [37].

In Europe, Germany and Sweden have led in advancing catenary truck technology, having invested in pilot projects to test and validate its potential on public roads. Since 2017, these countries have collaborated alongside France to further develop and implement this innovative solution. Sweden completed the world’s first trial of an overhead Electric Road System (ERS) on a public road. A 2 km electrified section north of Stockholm was built at approximately £10 million. Meanwhile, Germany has undertaken significant investments in catenary infrastructure, conducting pilot projects along major highways near Frankfurt, Lübeck, and Baden-Württemberg, with electrified segments ranging between 6 km and 10 km. The average construction cost was approximately £1.29 million per lane-km, without notable health, safety, or operational risks [56] .

Outside of Europe, jurisdictions are making progress in deploying catenary technology. In California, pilot projects funded through the Clean Transportation Program are being implemented as part of the state’s effort to support clean mobility solutions. In the United Kingdom, the Center for Sustainable Road Freight assessed the feasibility of catenary systems in 2020, estimating that electrifying 7,500 km of major roads could power 65% of heavy goods vehicle travel by the late 2030s, with an estimated investment of £19.3 billion. Moreover, the UK Department for Transport (DfT) is now considering a 20 km stretch of road near

Scunthorpe for a potential trial of electric road systems[56].

While catenary technology holds promise for the electrification of heavy-duty transportation by reducing battery size, weight, cost, and recharging time, it presents several challenges. Unlike fixed rail systems, catenary trucks can change lanes, requiring precise alignment with overhead wires, which increases the risk of damage and wear. To address this, advanced geofencing systems, lane-keeping assistance, and sensor-equipped pantographs monitor alignment and wear conditions to ensure optimal operation. Safety concerns also arise due to the high voltage of catenary lines (around 600V) over public highways, necessitating technologies such as wire break detection and automatic earthing systems to prevent accidental high-voltage exposure. Additionally, ice accumulation on the wires can cause electrical arcing, but this issue is effectively managed by mature de-icing techniques developed from similar cold-climate technologies [106, 56].

Hydrogen Fuel Cell Vehicles: Hydrogen fuel cell vehicles operate by storing hydrogen in pressurized tanks, which is then converted into electricity through a chemical reaction within the fuel cells. The generated electricity is stored in a small onboard battery that powers the electric motors and drive axles. With an efficiency of approximately 31%, FCEVs offer a significant advantage over conventional diesel trucks, which have an efficiency rate of 21%. Moreover, when hydrogen is produced from renewable energy sources, FCEVs can reduce life cycle greenhouse gas emissions by up to 50% compared to gasoline-powered internal combustion vehicles, making them a promising solution for achieving zero-emission targets in the transportation sector[130, 6].

Hydrogen fuel cell technology is adopted and tested globally, with significant initiatives in North America and Europe. In Canada, the Alberta Zero Emissions Truck Electrification Collaboration project is a leading example, exploring the use of hydrogen fuel cells for long-distance trucking. In the United States, California has been testing hydrogen fuel cell vehicles through several pilot projects. By 2017, California had deployed 26 fuel cell electric

buses, including a fleet of 13, while commercial logistics giants like UPS and FedEx have been exploring hydrogen-powered Class 6 delivery trucks. Additionally, Toyota and Nikola Motor have introduced hydrogen-powered long-haul trucks for field testing. In Europe, projects such as H2Haul and H2-Share are actively assessing the performance of hydrogen fuel cell technology in real-world heavy-duty applications, further driving the global development of this technology [93, 99].

Despite its potential, hydrogen fuel cell technology faces several significant challenges, delaying the initial target of achieving a 2.5% adoption rate for hydrogen-powered heavy-duty trucks to 2030. A primary obstacle is the lack of infrastructure, particularly in the heavy-duty sector. As of 2020, only 60 hydrogen refueling stations existed in the U.S., mostly serving light-duty vehicles, while Canada had just five stations in British Columbia and one each in Alberta, Ontario, and Quebec. Additionally, hydrogen’s low energy density complicates storage, requiring high pressures, extremely low temperatures, or chemical processes for efficient containment [111, 74, 123, 45]. Financial and technical barriers persist, with green hydrogen making up less than 1% of the global supply [106].

Advanced Bio-Fuels: Natural gas, referred to as biogas, is considered a viable solution for reducing GHG emissions in the transportation sector, as it has approximately 25% less carbon footprint compared to conventional fuels. Natural gas is available in different forms, including compressed (CNG) and liquefied natural gas (LNG), both of which are used in the transportation industry. Biomethane, a type of biogas, is a gaseous fuel produced through the anaerobic digestion of organic materials or the capture of landfill gas. During production, impurities such as hydrogen sulfide and moisture are removed, resulting in a methane-rich gas with a higher concentration than conventional biogas [112]. Renewable natural gas (RNG) is an upgraded form of biomethane, processed to meet pipeline quality standards, making it suitable for use as a transportation fuel in the form of CNG or LNG [113].

RNG offers several advantages over conventional natural gas, with its renewable nature

being a key benefit. Produced from organic waste, RNG reduces dependence on fossil fuels and significantly lowers the carbon footprint. While typically more expensive than conventional natural gas, RNG can be competitive with other energy sources including electricity, gasoline, and diesel, especially in areas without natural gas services. Additionally, it allows for the continued use of existing natural gas infrastructure while delivering the environmental benefits of renewable energy[113].

In Canada, natural gas infrastructure is gradually expanding, although RNG availability remains limited. Also, there are currently 37 stations supplying CNG and LNG across the country, with only nine of these stations support RNG [23]. Given The federal and provincial governments action to promote this expansion, Québec has set a goal to reach a 10% share of RNG in its natural gas distribution by 2030 [106]. Ontario has also made strides in RNG production, with projects such as the biogas upgrading facility at Toronto’s Dufferin Solid Waste Management Facility, and aims to produce 52.6 million cubic meters of RNG annually across multiple sites [113].

Despite the potential of natural gas and RNG to reduce GHG emissions by 16%, several limitations must be considered [132]. Natural gas engines tend to be less efficient than diesel engines, and methane emissions can occur during both the production and usage stages, which can significantly offset the GHG benefits. Methane has a global warming potential 34 times greater than CO₂ over a 100-year period, and any leakage during fuel production or use can greatly reduce the environmental advantages of CNG and LNG [132, 17]. Additionally, life-cycle analysis shows that while CNG and LNG do offer GHG reductions compared to diesel, these reductions are relatively modest, at 11.17% for CNG and 5.18% for LNG. Therefore, The overall benefit of RNG is highly variable and dependent on effectively managing methane emissions throughout the fuel cycle[148].

We have chosen to focus on BETs for this study due to their distinct advantages. Unlike hydrogen fuel cell trucks, which face challenges such as limited refueling infrastructure and

high energy costs, BETs benefit from a rapidly expanding network of charging stations and decreasing battery costs. Additionally, the deployment cost of charging stations is significantly lower than the infrastructure required for an electric highway corridor equipped with a catenary system. With advancements in battery technology, BETs are increasingly capable of meeting the range and payload requirements for long-haul transportation. Moreover, as BETs emit no greenhouse gases, there is no concern about methane emissions and their impact on climate change, making this technology the ideal choice for further modeling and methodology in our study.

2.4.2 Initiatives and incentives

Driven by international commitments to reduce transportation-related emissions, different countries have set ambitious targets to transition MHDVs to zero-emission alternatives. Sixteen nations, including Canada, are pursuing 100% zero-emission sales for new trucks and buses by 2040 [28]. Norway has set a goal of achieving 50% zero-emission truck sales by 2030, while Chile aims for full electrification of all new medium- and heavy-duty trucks by 2045. California’s Advanced Clean Trucks regulation mandates an increase in zero-emission truck sales, supported by nearly \$3-billion funding between 2021 and 2025 for both zero-emission trucks and the necessary infrastructure. By 2035, California aims for zero-emission vehicles to represent 55% of Class 2b-3 truck sales, 75% of Class 4-8 straight truck sales, and 40% of truck-tractor sales. Austria has committed to fully electrifying its truck fleet by 2035, while Australia targets net-zero emissions by 2050, including a complete phase-out of internal combustion engine truck sales by 2040. Major industry leaders, such as Mercedes/Daimler and Scania, have also pledged to achieve 100% zero-emission truck sales in Europe by 2039 and 2040, respectively [119].

In Canada, the target is to ensure that 35% of total new medium- and heavy-duty vehicle

sales are zero-emission by 2030. Additionally, the government is developing regulations requiring 100% of new medium- and heavy-duty vehicle sales to be zero-emission by 2040 for specific vehicle categories, based on feasibility assessments. Interim targets are also being considered, with an estimated 39,000 new medium- and heavy-duty zero-emission vehicle sales by 2030 [27].

Countries worldwide are investing heavily to accelerate the adoption of medium- and heavy-duty zero-emission vehicles to reduce greenhouse gas emissions from the transportation sector. The European Union (EU) has been a leader in this effort, providing substantial financial support. Germany offers up to 80% subsidies on the additional costs for zero-emission trucks and related infrastructure, while Ireland provides incentives for 700 low-emission trucks and 300 electric buses by 2025. Denmark has implemented tax incentives for trucks based on CO₂ emissions, effective in 2025, to promote cleaner options. Japan has also committed USD 120 million to support the electrification of heavy-duty vehicles and taxis. Other countries like Italy, the Netherlands, and Croatia have also introduced subsidy schemes to facilitate the adoption of zero-emission HDVs [76].

In the United States, the Inflation Reduction Act allocates \$1 billion specifically for heavy-duty vehicles and related infrastructure and also is also actively implementing various pilot projects, including the deployment of fuel cell electric buses. California has dedicated 70% of its charging infrastructure funding to HDVs, demonstrating a strong focus on electrifying heavy transport. The United Kingdom and Australia have similarly directed funding towards HDV infrastructure under their national initiatives, such as the Future Fuels Program in Australia. Additionally, countries like New Zealand, Japan, and China have set specific targets for reducing emissions from heavy transport. For instance, Japan aims to introduce 5,000 electric HDVs by 2030, while New Zealand targets a 35% reduction in freight transport emissions by 2035. Such incentives and targets reflect a strong global commitment to advancing the adoption of zero- or low-emission heavy transport [76].

In Canada, both the federal and provincial governments have introduced a range of incentives to promote zero-emission MHDVs. Federally, the government published the Action Plan for Clean On-Road Transportation in 2023, which includes a target of 35% of new MHDV sales to be zero-emission by 2030, and 100% by 2040 for specific vehicle categories. The Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) program allocates \$547.4 million over four years to help bridge the cost difference between zero-emission and traditional combustion vehicles. Furthermore, the 2022 federal budget provided \$545.7 million for purchase incentives and \$119.6 million to expand the Green Freight Program, which aims to support assessments and retrofits for ICE vehicles used in freight. The budget also included \$33.8 million to assist provinces in developing regulations and conducting safety tests for long-haul zero-emission trucks [27, 3].

Provincially, British Columbia's CleanBC Go Electric Medium- and Heavy-Duty Public Charger Program provides \$19.5 million in funding to increase the number of fast chargers across the province, while the Speciality Use Vehicle Incentive Program offers rebates of up to \$100,000 for on-road zero-emission MHDVs. In Quebec, the "Transportez vert" program offers comprehensive support, including covering up to 50% of energy management and technology acquisition costs and providing subsidies for electric vehicle purchases and infrastructure. The Écocardionnage subsidy program, which funds the acquisition of electric MHDVs, and the Quebec Ecoleader subsidy, which supports consulting and fleet electrification, also help facilitate the transition to zero-emission vehicles [149, 3].

2.4.3 On-duty Regulation for Commercial Vehicle

On-duty regulations for commercial truck drivers in Canada are designed to ensure both road safety and driver well-being, with a particular focus on managing driver fatigue. These regulations vary based on geographical regions, dividing Canada into northern and southern

zones at Latitude 60°N shown in Figure 2.6. This division reflects the distinct demands and conditions of each area. Provinces south of Latitude 60°N, such as British Columbia, Ontario, and Manitoba, are more densely populated and face higher transportation demands due to greater economic activity and population density. In contrast, northern regions above Latitude 60°N, characterized by sparser populations and longer distances between settlements, may have different regulatory requirements to address these unique challenges.



Figure 2.6: : Latitude 60° North

According to these regulations, commercial truck drivers are restricted to a maximum of 13 hours of driving per day, with an overall on-duty limit of 14 hours. This on-duty time includes not only driving but also other work-related tasks, such as refueling, loading and unloading cargo. The rules also mandate a minimum of 8 consecutive hours of off-duty time before a driver can begin their next shift, ensuring they have sufficient rest to prevent fatigue-related incidents. Additionally, regulations prohibit drivers from operating a vehicle if more than 16 hours have passed since their last 8-hour rest period, ensuring compliance with mandated rest intervals to support road safety and driver health. In the high-demand southern regions, where commercial activity is heavily concentrated, this requirement addresses the challenge of balancing the logistical demands of the transportation sector with maintaining safe and sustainable driving practices[20].

2.4.4 Electric Vehicle Routing problem

Electric trucks face significant challenges due to their limited range and the importance of timely deliveries, while offering a sustainable alternative for freight transportation. Unlike conventional vehicles, electric trucks require periodic stops for recharging, which can extend delivery times and affect schedules. Determining the shortest route minimizes travel distances, reduces energy consumption, and ensures access to charging stations, maintaining operational efficiency. Additionally, resting stops for drivers further add to the total delivery time. Therefore, route optimization for electric trucks must carefully balance the shortest path with strategic planning around charging and resting stops. Methods such as the Shortest Path Problem (SPP) and the Electric Vehicle Routing Problem (EVRP) are widely used to address these challenges, combining route efficiency with the need for charging and rest to optimize both time and distance.

Shortest path algorithm, introduced by Dijkstra, designed to identify most efficient and fastest route between two points [50]. Dijkstra’s algorithm, proposed in 1956 by Edsger W. Dijkstra, is a graph-based approach widely used in network optimization and routing problems. It iteratively selects the node with the smallest tentative distance, calculates the shortest distances to its neighbors, and updates them if a shorter path is found. The algorithm ensures efficiency by leveraging a priority queue to organize unvisited nodes. Dijkstra’s algorithm has numerous applications, including GPS navigation systems, telecommunication networks, and transportation planning, where it calculates optimal paths in weighted graphs [51, 44]. Building on a generalization of Dijkstra’s shortest path algorithm, Baum et al. utilized the Bicriteria Shortest Path Algorithm [69] to develop a specialized framework for identifying optimal constrained shortest paths for electric vehicles, relying exclusively on the initial charge and avoiding the need for en-route charging. This framework considers speed adaptation and incorporates battery constraints while excluding charging stops [12]. Tu et

al. have put a step forward to minimize reliable travel time, while also ensuring that energy consumption stays within the driving range constraint. They tackle the constrained reliable shortest path problem in urban transportation networks, aiming to design an EV navigation system that takes into account traffic flow and weather conditions as factors influencing energy consumption [140]. By taking into account en-route charging stops, Jafari et al. propose a novel approach for routing electric vehicles in stochastic networks to develop the EV shortest path problems. The study aims to minimize the generalized cost while ensuring a minimum level of reliability, considering the possibility of visiting at least one charging station during the trip to find the optimal path. To solve the problem, authors propose the generalized dynamic programming approach, which is a variant of the Bellman-Ford algorithm [78]. As a new factor, charging station availability is added to make the problem more realistic by Shen et al. [129]. Based on the classic Dijkstra algorithm, they proposed an energy-efficient and reliable path-finding algorithm for electric vehicles in stochastic road networks that considers factors such as energy consumption, travel time, charging station availability, and probability of completing the trip without running out of energy.

The Vehicle Routing Problem (VRP) attempts to identify the optimal order for visiting customers while beginning and ending at a depot to reduce travel time or distance [11]. With the advancements in electric vehicles, the field of study has developed and defined the electric vehicle routing problem (EVRP), as the VRP subset. The EVRP aims to identify the optimal energy, cost, or time-efficient route in a network, considering various non-linear factors such as electric vehicle range, charging time, and traffic conditions [150]. Kobayashi et al [88] is one of the first to integrate concrete charging points into the electric vehicle routing problem to minimize travel costs. By offering a route that incorporates accessible charging stations, the proposed EV Assist Route addresses concerns about limited range and sparse charging infrastructure for EVs. Considering the time windows, Li et al. propose a mixed heuristic planning model to conduct a detailed study on the routing problem to determine an optimal

urban distribution route that satisfies electric vehicle and customer time window limitations [94]. In the following, coordinating the routing and recharge scheduling while minimizing operation and battery degradation is Barco et al. [10] effort, employed as an airport shuttle service case study. Furthermore, Keskin et al. [86] acknowledge that charging stations have limited capacities and that newly arrived vehicles may have to wait before recharging. To tackle this problem, the Electric Vehicle Routing Problem with Time Windows was modeled, and the solution was proposed to minimize the cost of vehicles, drivers, and energy while also considering penalties for late arrivals.

This study aims to address the issue of providing resting stations for electric vehicle drivers, which arises due to the restricted on-duty hours outlined in the Canadian government’s commercial vehicle driving legislation. The combination of this constraint with the limited battery capacity of electric vehicles has prompted the proposal of a solution. This approach can minimize the total travel time for drivers and help them adhere to the on-duty hour restrictions.

2.5 Research Gap and Study Contribution

Passenger Electric Vehicles addresses critical gaps in the deployment of passenger EV charging infrastructure by developing a comprehensive optimization framework tailored to urban areas, specifically Toronto. While previous studies have explored EV charging station placement, there is a clear need for models that integrate detailed local data, such as EV ownership, existing infrastructure, and travel patterns, to make more informed decisions regarding charger locations and types. The proposed model fills this gap by accounting for variability in home charger access, the distribution of EV ownership across wards, and the diversity of chargers required to accommodate different trip purposes. By incorporating both Level 2 and DC fast chargers, the model ensures the energy needs of EVs and PHEVs are met

efficiently. This study emphasizes the importance of strategically locating charging stations to influence charging behavior and alleviate range anxiety to increase EV adoption.

Medium to Heavy-duty Electric Trucks addresses critical gaps in optimizing charging and route planning for MHDEVs along the Highway 401-A20 corridor, from Rivière-du-Loup to Windsor. A key challenge in electric truck adoption is balancing limited range with delivery deadlines, while also adhering to Canadian on-duty regulations requiring rest stops. Existing studies often overlook the combined impact of charging station availability, driver rest, and battery constraints. This study develops a comprehensive framework that integrates these factors—initial state of charge, battery consumption rates, charging station availability, and rest stops—to minimize travel time and optimize freight operations.

2.6 Chapter Summary

This chapter provided a comprehensive review of the key aspects of EV adoption, focusing on passenger electric vehicles and electric trucks, charging infrastructure, and route optimization strategies. It began with an overview of the current and projected market share of different EV types, highlighting the rapid global shift toward sustainable transportation, with a particular emphasis on Canada. The discussion then moved to the importance of expanding charging infrastructure to support the growing number of EVs, analyzing both public and private investments and the challenges in deploying charging stations for long-haul trucks. The optimization of charging infrastructure was explored through node-based and flow-based models, essential for strategically placing charging stations in areas with varying transportation demands. The chapter also examined the range limitations of electric trucks, emphasizing the critical need to find the shortest path to minimize delivery times while accounting for necessary charging and rest stops. Route optimization models, such as the SPP and EVRP, were introduced as effective strategies for balancing these challenges.

Additionally, the chapter discussed the advantages of battery electric trucks over other zero-emission technologies, citing their expanding infrastructure, lower costs, and zero emissions as key reasons for their selection in this study. The review concluded with examining Canadian on-duty regulations for commercial truck drivers, underscoring the importance of managing driver fatigue and adhering to regulatory requirements. Overall, this chapter established a solid foundation for further research into electric truck technology, charging infrastructure, and route optimization.

Chapter 3

Study Data

3.1 Passenger Vehicles

The widespread adoption of EVs is hindered by several key barriers, with high purchase costs and range anxiety as primary concerns among prospective users. Addressing these challenges requires a well-planned and adequately funded charging network to support the growing number of EVs on the road. Strategic infrastructure planning is essential not only to alleviate range anxiety but also to drive the broader expansion of the EV market, enhancing the convenience and feasibility of using EVs.

This research concentrates on optimizing the deployment of EV charging stations in the city of Toronto, facilitating the shift to a low-emission transportation system. The study fills gaps in existing EV infrastructure models by considering factors specific to Toronto, such as the distribution of EV ownership, access to home charging, and detailed travel patterns. We propose an optimization framework to identify the ideal number and location of charging stations, aiming to minimize installation costs while accommodating both current and projected demand. This approach enhances the flexibility of EV charging networks and provides a model applicable to other urban areas pursuing similar objectives.

This section provides a detailed overview of the data sources utilized in this study. It begins by outlining the 25 wards of Toronto as the foundational geographic divisions for the analysis. Following this, we explore key datasets, including EV charger location data, EV ownership statistics, and information from the Transportation Tomorrow Survey. Each data

source is comprehensively described to explain its application within our research.

3.1.1 Geographic Framework: Toronto's Wards & FSA

Toronto's ward system serves as geographic divisions to facilitate local governance, ensuring effective representation and equitable distribution of resources. The city has restructured its ward boundaries to reflect population changes and evolving needs over time. From 2014 to 2018, Toronto operated with a 44-Ward Model, based on census data and community demographics. In 2016, following the Toronto Ward Boundary Review, a new 47-Ward Model was proposed and approved by City Council. This model aimed to accommodate population growth and provide more equitable representation. However, before its implementation, the provincial government enacted Bill 5, the Better Local Government Act, which reduced the number of wards to 25. This new Model, shown in Figure 3.1a, has been in effect since the 2018 municipal election and continues to serve for the 2022-2026 term. [115, 116, 117].

While EV ownership data was categorized by FSA rather than by ward, the dataset was adjusted to align with ward boundaries to ensure accuracy in the analysis. FSA is a geographical unit used in Canada, represented by the first three characters of a postal code, depicts in Figure 3.1. The first character, a letter, indicates the province or territory, with larger provinces having region-specific identifiers (e.g., "K" for Eastern Ontario and "M" for Metropolitan Toronto), while smaller territories such as Nunavut and the Northwest Territories share the letter "X." The second character, a numeral, distinguishes urban and rural areas, with "0" representing rural regions and other digits indicating urban zones. The third character, in combination with the first two, identifies a more specific geographic area, such as a particular rural district, a medium-sized city, or a section of a larger metropolitan area [114].

Dissemination Areas (DAs) are another standard geographic unit in Canada, consisting

of uniformly sized areas used for the distribution of statistical data. A DA typically includes 400–700 households and can vary in size, from smaller than a postal code to larger than an FSA in rural regions. In rural areas, DAs may offer less detailed information compared to FSAs. DAs are the second smallest standard geographic unit for which demographic data is available and the smallest unit for public datasets [104].

This study adopts a ward-level framework as the foundation for geographic analysis, enabling a cohesive evaluation of EV trip distributions, existing charging infrastructure, and EV ownership. Although finer geographic units like FSAs and DAs offer more granularity, analyzing data at these levels was deemed unnecessary for the scope of this research. Additionally, EV trip distribution data from the Transportation Tomorrow Survey is available only at the ward level, necessitating alignment of the geographic analysis with this dataset. Consequently, the ward-level framework was chosen to ensure consistency and relevance to the study’s objectives.

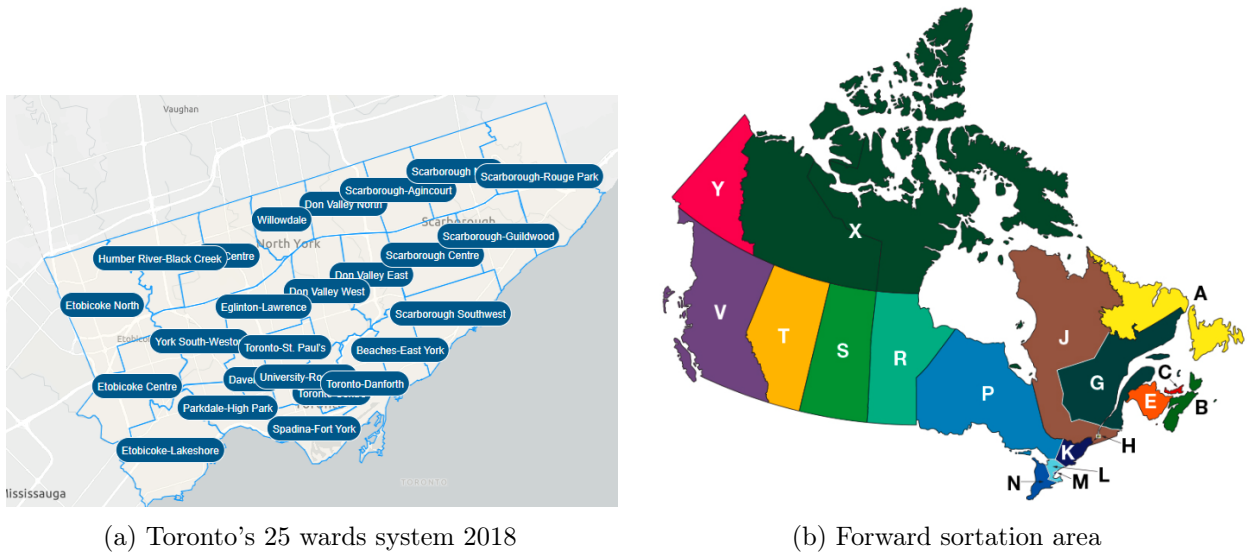


Figure 3.1: Geographical distribution systems: (a) Toronto’s 25 wards system, (b) forward sortation area

3.1.2 EV charger Location Data

The EV charger location data used in this study is sourced from Natural Resources Canada (NRCan), offering an up-to-date database of charging stations across the country. NRCan gathers this data from various sources, including trade media, infrastructure providers, fuel suppliers, and partnerships with original equipment manufacturers (OEMs). This comprehensive dataset contains information on station locations, EV charging ports, and connector types and is shown in table 3.1 [22]. Charging stations are categorized by accessibility into either public or private. Former stations are accessible to all EV users, while later ones are restricted to specific users, such as employees at a workplace, or residents of a private property. The dataset also includes information on each station’s availability, detailing any limitations such as time restrictions or access requirements. Furthermore, vehicle accessibility is categorized by station, indicating which vehicle classes (ranging from passenger vehicles to heavy-duty trucks) can physically access the charging infrastructure based on station design, parking layout, and space constraints [22]. We used this data to map each charger and assess the availability of different charger types and the energy they provide in each ward.

3.1.3 EV Ownership Data

For EV ownership, we used the MTO dataset outlining the distribution of BEVs and PHEVs across Ontario, segmented by FSA [24] shown in table 3.1. To align this data with the ward-level analysis, we adapted the FSA data into ward-specific estimates by applying weighted averages based on the geographic distribution of postal code areas. This approach allowed for a more accurate estimation of EV charging demand within each ward.

Table 3.1: Charging stations distribution and EV ownership by ward

	Ward Name	BEVs	PHEVs	Stations	Lev2	DC
1	Etobicoke North	578	–	24	51	2
2	Etobicoke Centre	462	211	5	15	–
3	Etobicoke-Lakeshore	654	268	25	93	24
4	Parkdale-High Park	404	255	6	12	1
5	York South-Weston	143	–	7	4	9
6	York Centre	291	–	16	33	3
7	Humber River-Black Creek	139	–	2	31	–
8	Eglinton-Lawrence	643	–	17	32	6
9	Davenport	242	119	2	4	–
10	Spadina-Fort York	697	189	136	469	28
11	University-Rosedale	540	–	37	161	4
12	Toronto-St. Paul’s	476	168	13	58	1
13	Toronto Centre	271	–	50	212	20
14	Toronto-Danforth	405	–	12	60	–
15	Don Valley West	965	–	11	29	3
16	Don Valley East	445	–	10	15	2
17	Don Valley North	437	186	23	37	28
18	Willowdale	562	251	21	80	2
19	Beaches-East York	352	223	17	34	–
20	Scarborough Southwest	246	131	4	14	3
21	Scarborough Centre	170	82	9	21	5
22	Scarborough-Agincourt	109	47	2	18	–
23	Scarborough North	216	95	8	9	6
24	Scarborough-Guildwood	165	103	5	34	2
25	Scarborough-Rouge Park	389	215	8	56	4

3.1.4 Electric Vehicle’s Trip Distribution

The distribution of electric vehicle trips within Toronto was derived using data from the Transpotation Tomorrow Survey, providing a comprehensive understanding of travel patterns across the Greater Golden Horseshoe Area. TTS is a travel survey conducted every five years, capturing extensive data on travel behaviors and organizing it into household, person, and trip categories, as well as transit route information [47].

The 2016 dataset represents the most recent publicly available version of this survey.

To align with the study’s objectives, trips were filtered to include only those originating from home, with destinations categorized for market/shop or work purposes, as detailed in Tables 6.1 and 6.2. This approach allowed us to determine the number of trips from home to other wards with these specific travel purposes. Furthermore, we prioritized auto drivers as the primary mode of transportation among other options such as school buses and bicycles. The extracted data was formatted as a Cross Tabulation Query in Excel, with rows representing the origin and columns representing the 2018 Toronto destination wards, showing the number of filtered trips by purpose. Additionally, the survey provided demographic information, including household characteristics (such as dwelling types and number of vehicles per household) and population properties (age, ethnicity, etc.), provides a foundation for future research aimed at predicting EV adoption trends for 2023 and beyond.

3.2 Medium and heavy duty electric trucks

3.2.1 Study Area

This study focuses on Highway 401, a key corridor of Canada’s transportation network, extending 828 kilometers from Windsor, Ontario, to the Quebec border. Known as the Macdonald–Cartier Freeway, Highway 401 plays a primary role in the Quebec City–Windsor Corridor, supporting over half of Canada’s population. Its strategic role is further highlighted by the section through Toronto, which is among the busiest in North America. With traffic volumes exceeding 450,000 vehicles per day, this key artery is essential for the efficient movement of goods and people across Ontario[41].

The study also examines Autoroute 20 (A20), Quebec’s longest highway, spanning 585 kilometers. The A20 is divided into two segments, separated by a 57-kilometer gap: a primary section extending 540 kilometers from the Ontario border to Trois-Pistoles, and a shorter northern section of 44 kilometers[42]. In conjunction with Highway 401, A20 facilitates regional and national trade through the connectivity of major transportation hubs. These hubs include Toronto Pearson Airport, Canada’s largest air cargo facility, which processes over 300,000 tonnes of cargo annually, as well as Pierre Elliott Trudeau and Mirabel International Airports, which handle over 160,000 tonnes of freight each year together. Furthermore, Hamilton International Airport, a significant domestic air cargo hub, manages 122,000 tonnes annually, underscoring the importance of A20 in enhancing the efficiency and capacity of Canada’s logistics network [25].

Highway 401 and A20 serve as vital arteries for international trade, connecting to the Windsor-Detroit border, one of North America’s most active trade corridors. The corridor connects to marine transportation hubs such as the Port of Montreal, Canada’s second-largest container port, which handles 41 million tonnes of cargo annually [26]. Furthermore, the corridor’s importance is further elevated by the upcoming opening of the Gordie Howe

International Bridge in fall 2025, which will strengthen connections between Michigan and Ontario [34]. These connections highlight the significance of the A20-Highway 401 corridor for both national logistics and international trade, underscoring its selection as a focus for medium- and heavy-duty vehicle deployment.

This study specifically focuses on the Highway 401–A20 segment that connects Rivière-du-Loup, Quebec, to Windsor, Ontario 3.2. Given the strategic importance of this corridor, an analysis of existing resting locations and charging stations is undertaken to evaluate the availability of electric supply for MHDEVs. To address the identified needs, the study also considers the implementation of new charging infrastructure at suitable resting areas along this route to better serve MHDEV requirements. Further discussion includes the data sources utilized and their relevant properties, providing a foundation for understanding the current infrastructure and planning improvements.

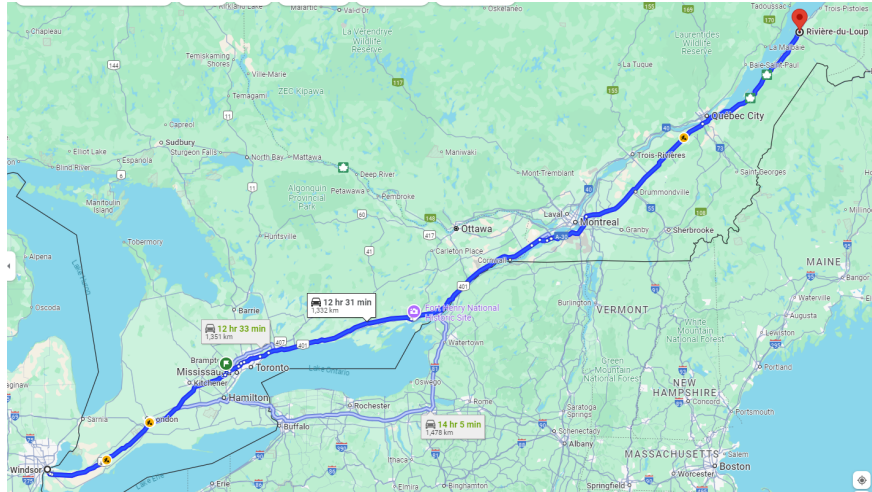


Figure 3.2: Study area: Highway 401–A20, connecting Rivière-du-Loup, Quebec, to Windsor, Ontario

3.2.2 Charging Stations Data

Charging station data was extracted from the Natural Resources Canada (NRCan) dataset. The data was filtered to include only those stations suitable for medium-duty (Class 3-5) and heavy-duty (Class 6-8) electric trucks. According to the filtered dataset, there are 19 Level 2 and DCFC stations available in Ontario, while Quebec hosts 74 such locations. In Ontario, these include 41 charging output with connectors such as J1772, CCS, CHAdeMO, and J3400, whereas Quebec has 183 ports with similar configurations [22].

The power output for Level 2 chargers is considered to be within an average range of up to 50 kW, whereas DC fast chargers are assumed to provide between 50 kW and 350 kW. For the purposes of this study, which focuses on the Highway 401–A20 corridor, only stations within a 10 km radius of the highway were considered. However, stations located within city centers, excluding Montreal, were not included in the analysis. Given that Montreal serves as a crucial intersection connecting A20 to Highway 401, the charging stations in this city were incorporated. Ultimately, 19 station locations were identified in Quebec along with 5 stations in Ontario. These stations contain data regarding various attributes, as shown in Figure 3.4.

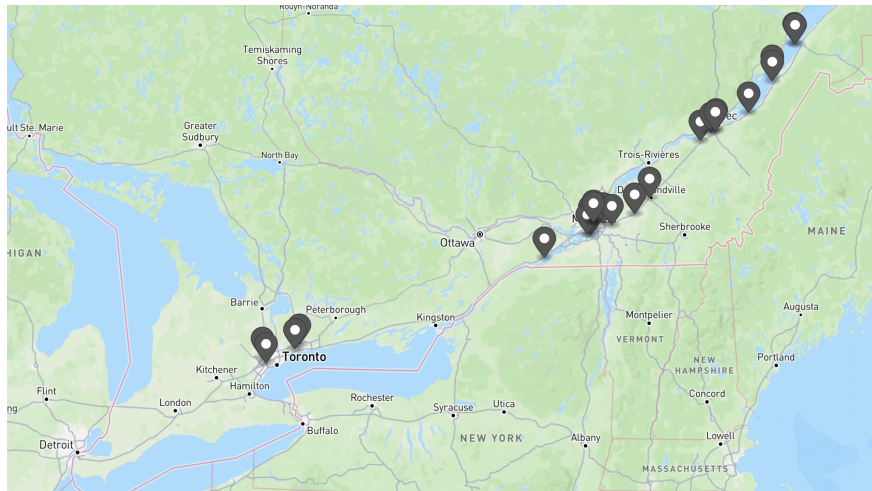


Figure 3.3: Charging station location for medium to heavy- duty trucks in Quebec and Ontario

3.2.3 Resting Locations Data

Resting location data for trucks was obtained from MTO through a data request to the Systems Analysis and Forecasting Office. This dataset provides information on truck plazas in both Quebec and Ontario. Truck stops or plazas refer to business facilities catering to long-distance truck deliveries, which typically include fuel pumps for heavy trucks/lorries, and may also offer amenities such as restaurants, service facilities, and sleeping and showering areas. Therefore, these locations have been considered as rest stops for the purposes of this study. Since the focus of this research is the Highway 401–A20 corridor, only locations within a 10-kilometer distance from the main road were included. Based on this criterion, 37 resting locations were selected, as shown in the figure below.

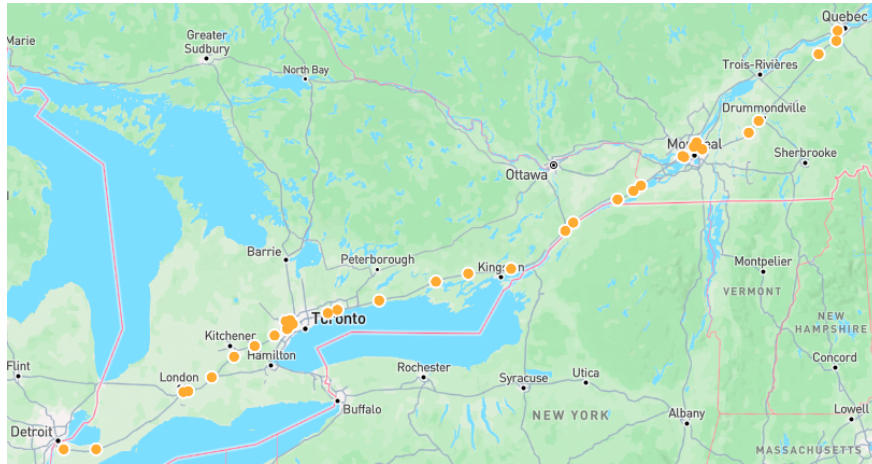


Figure 3.4: Selected 37 truck resting locations within 10 km of the Highway 401–A20 corridor (based on the MTO dataset)

3.3 Chapter Summary

This chapter is data-focused, utilizing various datasets to evaluate the deployment of EV charging infrastructure in Toronto and along the Highway 401-A20 corridor for MHDEVs. For passenger vehicles, data on EV ownership, charging station locations, and travel patterns

across Toronto's 25 wards were analyzed to determine optimal charging station placements. The study also examines the Highway 401 and A20 corridors, essential for national and international trade, to assess existing charging stations and resting areas for MHDEVs. Charging station data was filtered to focus on locations suitable for medium- and heavy-duty trucks within 10 kilometers of the highway, while resting location data was sourced from the Ministry of Transportation of Ontario.

Chapter 4

Modelling Methodology

This chapter delves into the modeling and methodology employed to determine the optimal locations for deploying EV charging infrastructure for passenger electric vehicles across Toronto’s 25 wards and for MHDEVs along the Highway 401-A20 corridor.

4.1 Passenger Vehicles

This study introduces a methodology that integrates data collection with optimization modeling to guide the deployment of EV charging stations across Toronto. The approach aims to provide a comprehensive understanding of the existing infrastructure landscape while anticipating future EV charging needs. Initially, we analyzed EV ownership, charger locations, and travel patterns to gain detailed insights into current electricity demand, the availability of charging infrastructure, and their geographic distribution. This analysis resulted in the mapping outcomes presented in 5.1d using Mapbox, as discussed in the following chapter. Subsequently, we developed an optimization model to determine the optimal number and types of chargers needed at each ward. By integrating empirical data with predictive analytics, we aim to provide practical strategies that enhance both the accessibility and effectiveness of EV charging networks in urban settings.

This proposed optimization model is designed to determine the optimal number of Level 2 and DCFC chargers needed to minimize the total installation costs while ensuring that the energy produced meets the demands of EVs and PHEVs. The model operates under

the assumption that individuals lacking access to home chargers will predominantly use public charging facilities at their destinations, such as workplaces or leisure locations. The model allocates charger types based on trip patterns, recognizing that the time spent at workplaces is generally sufficient for Level 2 charging, while shorter visits to locations such as malls or grocery stores are better suited for fast charging with DC chargers. This approach optimizes charger placement and types to effectively support EV owners without access to home charging.

$$\text{0Minimize } C_{total} = \sum_{i=1}^{25} (C^{Lev2} n_i^{Lev2} + C^{DC} n_i^{DC}) \quad 4.1$$

Subject to:

$$e = 0.5 \text{ kWh/km} \times 23 \text{ km/day} \times 30 \text{ days/month} \quad 4.2$$

$$E_i = v_i \times r \times e \quad \forall i \quad 4.3$$

$$E_i \leq \sum_j (x_{ij}^W h^W R^{Lev2} + x_{ij}^L h^L R^{DC}) \quad \forall i \quad 4.4$$

$$\sum_i x_{ij}^W h^W \leq (n_j^{Lev2} + N_j^{Lev2}) \times 12 \text{ hours} \times S_{Lev2} \times 5 \text{ days/week} \times \frac{30}{7} \text{ week/month} \quad \forall j \quad 4.5$$

$$\sum_i x_{ij}^L h^L \leq (n_j^{DC} + N_j^{DC}) \times 12 \text{ hours} \times S_{DC} \times 7 \text{ days/week} \times \frac{30}{7} \text{ week/month} \quad \forall j \quad 4.6$$

$$x_{ij}^W \leq T_{ij}^W \times \frac{v_i}{\text{vehicles}_i} \quad (\text{work trips per EV from ward } i \text{ to ward } j) \quad \forall i, j \quad 4.7$$

$$x_{ij}^L \leq T_{ij}^L \times \frac{v_i}{\text{vehicles}_i} \quad (\text{leisure trips per EV from ward } i \text{ to ward } j) \quad \forall i, j \quad 4.8$$

In the equations above, n_i^{Lev2} and n_i^{DC} represent the number of chargers of each type to be installed in ward i . The variable e calculates the required energy that an EV consumes over a month, which is determined by multiplying the required energy per kilometer by the

average daily commute distance specific to the city and the number of days in a month. E_i is the required energy in each ward, calculated as the number of EVs in ward i multiplied by the percentage of garage orphans times e . The decision variables x_{ij}^W and x_{ij}^L represent the number of work or leisure trips from ward i to ward j where EVs will charge at their destination. h^W and h^L are the average time durations spent at the destination of work and leisure trips, respectively. R^{Lev2} and R^{DC} are the output power of Level 2 and DC chargers in kW.

The constraint 4.4 ensures that the required energy E_i at each ward i does not exceed the energy provided during the time spent at destinations for work or leisure trips in other wards where EVs are expected to charge. This constraint reflects the capacity of both Level 2 and DC chargers to meet the local demand.

Constraints 4.5 and 4.6 guarantee that the total time spent charging EVs, resulting from the number of trips leading to charging sessions at their destinations, does not surpass the cumulative operational capacity. This capacity is defined by the sum of the number of existing chargers plus the new chargers to be installed, multiplied by the assumed operating hours (12 hours per day), the availability rate of the chargers, and the number of days they are utilized. For DC chargers, this is calculated for all days of the month, whereas for Level 2 chargers, the calculation is based on the number of working days, reflecting typical usage patterns.

Finally, constraints 4.7 and 4.8 ensure that the trips x_{ij}^w and x_{ij}^L , representing the number of work and leisure trips from ward i to ward j where EVs will be charged, do not exceed the ratio of EVs to the total vehicle fleet multiplied by the total trips of all vehicle types from ward i to ward j for each respective purpose. This condition ensures that the planning of charger deployment is directly tied to the actual travel behavior and EV usage in each area.

The proposed methodology, initially tailored for the City of Toronto, can be adapted to other cities or regions by adjusting the input variables to reflect local conditions, such as EV ownership rates, trip distributions, and geographical divisions. For instance, instead of

using ward-level data, any available geographic subdivision can be utilized, provided that corresponding data is accessible. This adaptability ensures the methodology’s relevance and scalability, enabling its application across diverse urban and regional contexts to optimize EV charger deployment effectively.

4.2 Medium and Heavy-duty Electric Trucks

The proposed optimization model aims to determine the optimal schedule for medium- and heavy-duty electric trucks by factoring in driving regulations and the availability of charging stations along the Highway 401–A20 corridor. The model addresses two key challenges: range anxiety due to limited battery capacity and compliance with on-duty hours regulations, as mandated by Canada’s commercial vehicle driving laws (refer to section 2). Considering these constraints, the model identifies strategic locations where drivers can rest and recharge their vehicles, minimizing travel time while avoiding range anxiety and ensuring adherence to driving regulations. Additionally, the model accounts for vehicle-specific properties such as battery capacity, initial state of charge, and battery consumption rate, alongside infrastructure characteristics like charging station locations and charging rates, given the data from Natural Resources Canada[23].

4.2.1 Mathematical Modelling

Starting from the objective function in equation 4.9, the model considers the summation of transit time between stations and the maximum of charging or resting time at each stop k . The travel time includes x_{ij}^k , a binary decision variable that indicates whether the truck travels from node i to node j during the k -th stop, with a value of one if the travel occurs and zero, otherwise. T_{ij} represents the transit time between stations i and j . Additionally, Q^k denotes the maximum of the charging or resting time at each stop k , as the time spent at each

stop may be due to either charging or resting, with the longer duration being considered as the time spent at the stop, considered in the equations 4.12 and 4.13. Equation 4.10 defines the state of charge (SoC^{k+1}) upon departure from station $k + 1$ as follows: the state of charge (SoC^k) at the previous station, minus the energy consumed while traveling from station i to j , plus the energy replenished at station $k + 1$. The energy supplied at each station is a function of the charging time, demonstrated by y^{k+1} , and the charging capacity of the battery, denoted as R^{k+1} . In this study, we introduce the variable State of Fatigue (SoF) to quantify driver tiredness during a trip. The SoF is based on the Canadian government's on-duty regulations for commercial vehicles. According to these regulations, the maximum SoF is 14 hours, aligns with the maximum allowable on-duty hours for commercial vehicle drivers, after which an 8-hour rest period is mandated. These constraints are effectively incorporated in equations 4.20 and 4.21. Also, We track the SoF for drivers at each station upon departure, calculating as the SoF from the previous station while leaving the station, minus the time spent driving from station i to j , and subtracting the resting time z^{k+1} at the current station shown in equation 4.11. Additionally, as per Government of Canada regulations, refueling is considered part of on-duty hours. Consequently, the charging time at station $k + 1$, is added to the SoF . Equations 4.14-4.18 illustrate the flow within the network. Specifically, the first three equations (4.14-4.16) demonstrate that the input flow to each station must equal the output flow, ensuring the vehicle travels through all nodes to reach its destination D . Equations 4.17 and 4.18 ensure the vehicle starts its journey from the origin O and ends at the destination. Equation 4.19 sets boundaries for the vehicle's state of charge at each station k , ensuring sufficient battery charge for travel from station i to j . To allow the drivers to rest at designated locations and charge at equipped stations, Equations 4.22 and 4.23 are formulated with M as a large parameter. I_{cj}^k is equal to 1 if a charging station is available at the k_{th} stop in node j , otherwise it is zero. I_{Fj}^k indicates the availability of a resting location at the k_{th} stop in node j , with a value of one if available, otherwise zero. The remaining

equations ensure that the parameters x_{ij}^k and the variables I_{Fj}^k and I_{cj}^k are binary.

$$\text{minimize } \sum_{k=0}^{N+1} \sum_{i \neq j} (x_{ij}^k \cdot T_{ij} + Q^k) \quad 4.9$$

subject to:

$$SoC^{k+1} = SoC^k - \sum_{i,j,i \neq j} x_{ij}^k \cdot T_{ij} \cdot C_{i,j} + y^{k+1} \cdot R^{k+1}, \quad \forall k \in \{0, 1, 2, \dots, N+1\} \quad 4.10$$

$$SoF^{k+1} = SoF^k + \sum_{i,j,i \neq j} x_{ij}^k \cdot T_{ij} - z^{k+1} + y^{k+1}, \quad \forall k \in \{0, 1, 2, \dots, N+1\} \quad 4.11$$

$$y^k \leq Q^k, \quad \forall k \quad 4.12$$

$$z^k \leq Q^k, \quad \forall k \quad 4.13$$

$$x_{Oj}^k = \sum_{i,i \neq j} x_{ji}^{k+1}, \quad \forall j, k = 1 \quad 4.14$$

$$\sum_i x_{ij}^k = \sum_{i,i \neq j} x_{ji}^{k+1}, \quad \forall j, \forall 1 < k < K \quad 4.15$$

$$\sum_i x_{iD}^k = \sum_{i,i \neq j} x_{ji}^{k-1}, \quad \forall j, k = K \quad 4.16$$

$$\sum_j x_{Oj}^1 = 1, \quad 4.17$$

$$\sum_i x_{iD}^K = 1, \quad 4.18$$

$$\sum_{i,j,i \neq j} x_{ij}^{k+1} \cdot T_{ij} \cdot C_{i,j} \leq SoC^K \leq \max SoC, \quad \forall k < K \quad 4.19$$

$$\sum_k SoF^k \leq 14 \text{ hours of on-duty}, \quad 4.20$$

$$\sum_k z^k \leq 8 \text{ hours of off-duty}, \quad \forall k \in \{0, 1, 2, \dots, N+1\} \quad 4.21$$

$$y^k \leq M \cdot I_{cj}^k, \quad \forall k, j \in N \quad 4.22$$

$$z^k \leq M \cdot I_{fj}^k, \quad \forall k, j \in N \quad 4.23$$

$$x_{ij}^k \in \{0, 1\}, \quad \forall k \quad 4.24$$

$$I_{fj}^k \in \{0, 1\}, \quad \forall K \quad 4.25$$

$$I_{cj}^k \in \{0, 1\}, \quad \forall K \quad 4.26$$

$$4.27$$

4.2.2 Methodology and Flowchart

The algorithm begins by initializing key variables and incorporating inputs derived from the collected data. One primary input is the distance between charging stations, evaluated using the Government of Canada chargers location dataset and processed with Python's Geodesic function from the Geopy library. This distance data, combined with the truck's average velocity (set at 80 km/h), calculates the transit time between stations, denoted as T_{ij} [22].

Charging station locations form another input, represented by a binary variable (I_{cj}^k), derived from the Government of Canada dataset. This variable indicates whether a location contains a DCFC or Level 2 charger (value of 1) or not. The study assumes that trucks arriving at these stations can charge based on charger type availability, without accounting for queue lengths or the number of chargers at a location [22]. Similarly, resting area locations are represented by a binary variable (I_{fj}^k), sourced from the MTO dataset, which indicates whether a location is a designated resting area (value of 1).

Additional inputs include battery capacity and battery consumption rates, which vary by truck type, model, and manufacturer. These parameters are detailed in Table 5.2.

The allowable maximum and minimum state of charge (SoC) is considered as a percentage of the battery's capacity. To account for slower charging rates above 80% capacity, a buffer is applied, capping the maximum SoC at 90% to optimize battery utilization [58]. Additionally, a minimum SoC buffer of 10% is included to prevent complete depletion, ensuring sufficient reserve energy for the truck.

Driver constraints are addressed with a maximum state of fatigue (SoF) of 14 hours, reflecting the mandated on-duty limit, while a minimum SoF of 0 hours establishes the threshold for required rest duration. Furthermore, the initial state of charge and fatigue are included as inputs to define the starting conditions of the truck and driver at the beginning of the trip.

The algorithm iterates through stations k , sequentially evaluating SoC and SoF using equations 4.10 and 4.11, respectively, until a violation occurs. A violation is identified when SoC drops below the 10% of battery capacity or SoF exceeds the 14-hour limit. Upon detecting a violation, the algorithm backtracks and identifies the two nearest stations with available chargers ($I_{cj}^k = 1$) or resting facilities ($I_{fj}^k = 1$), depending on the type of violation, to address the issue.

If the violation is due to SoC , the algorithm evaluates the two nearest preceding stations to determine which one effectively delays subsequent violations. The algorithm begins by updating the SoC , ensuring it does not exceed the maximum allowable limit. If two hours of charging would surpass the maximum SoC , the truck is charged only until the maximum SoC is reached, and the charging time is adjusted accordingly to reflect the actual time required, which will be less than two hours. Conversely, if the updated SoC remains below the maximum limit, it is calculated as the product of the two-hour charging time and the charging rate at the selected station.

If the violation is due to SoF , the algorithm evaluates whether the station provides both charging and resting facilities. If both facilities are available and the charging time exceeds the resting time, the updated SoF is calculated as the current SoF plus the charging time minus the resting time, considering that charging is regarded as an on-duty activity under regulatory requirements. In contrast, if the resting time exceeds the charging time, the updated SoF is calculated as the current SoF minus the resting time. Furthermore, since the resting time cannot result in SoF dropping below the minimum SoF (which is set to 0

hours), if the updated SoF falls below the minimum SoF , the algorithm allows the driver to rest until the state of fatigue reaches the minimum threshold. In such cases, the resting time is updated accordingly and will be less than 8 hours. If an 8-hour rest does not bring SoF to the minimum SoF , the resting time is capped at 8 hours, and the SoF is updated accordingly.

If only a resting facility is available, the updated SoF is calculated as the current SoF minus the resting time, ensuring that SoF does not drop below the minimum state of fatigue.

Lastly, if only a charging facility is available, the SoF is updated due to on-duty regulations, with the updated SoF calculated as the current SoF plus the charging time.

After updating the SoC or SoF based on the violation type and the facilities available at the station, the algorithm evaluates which of the two selected stations is more likely to experience a further violation. The station where the next violation is expected to occur later is chosen. The updated SoC and SoF values are then applied to the selected station, replacing the previous values. The algorithm proceeds to the next station ($k + 1$). This iterative process continues until the truck reaches its destination.

The proposed methodology can be applied to other highway corridors within the province, such as Highway 11 connecting Ontario to Manitoba, as well as national and international corridors. This requires integrating data on existing charging infrastructure, truck stop locations, and vehicle-specific factors, such as initial state of charge and energy consumption rates. By incorporating these elements, the methodology ensures that the unique operational needs and travel patterns of medium- and heavy-duty vehicles are effectively addressed, facilitating strategic planning for charging networks tailored to long-haul freight corridors.

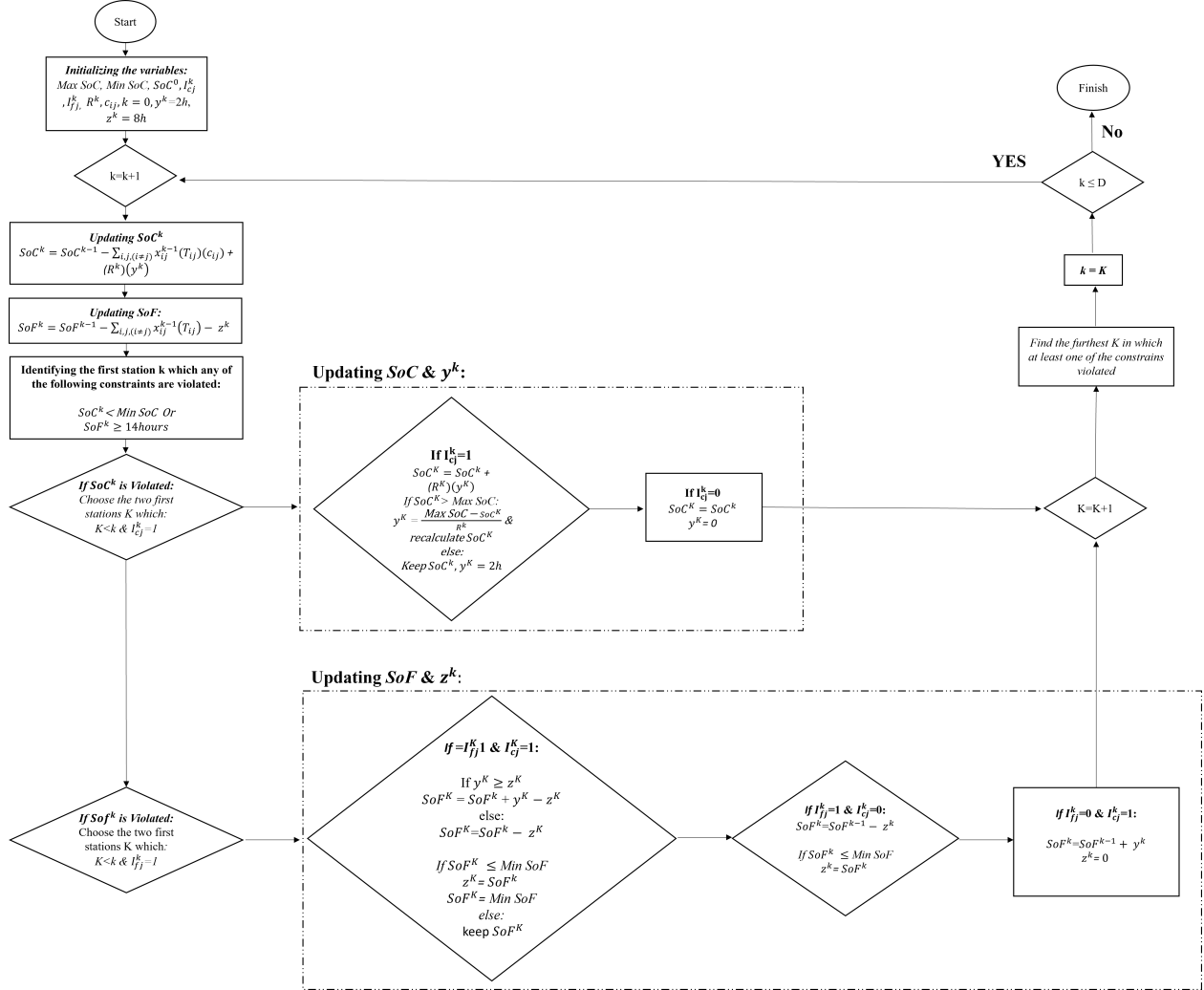


Figure 4.1: Flow chart: Steps for medium- and heavy-duty trucks considering on-duty regulations and charging constraints

4.3 Chapter Summary

This section provides a detailed overview of the mathematical modeling approach for passenger and medium-to-heavy-duty electric vehicle scenarios. For passenger vehicles, we developed a model within the 25 wards of Toronto, considering trip purposes, charger types, energy supply and demand at each ward, and incorporating garage orphans to enhance model realism. The second part outlines the mathematical modeling for medium- and heavy-duty trucks,

incorporating parameters such as battery consumption rates, initial state of charge, battery capacity, and charging station characteristics, including Level 2 and DCFC charging rates. Additionally, we integrated an on-duty regulation component to monitor drivers' fatigue, ensuring compliance with government-mandated limits on on-duty hours.

Chapter 5

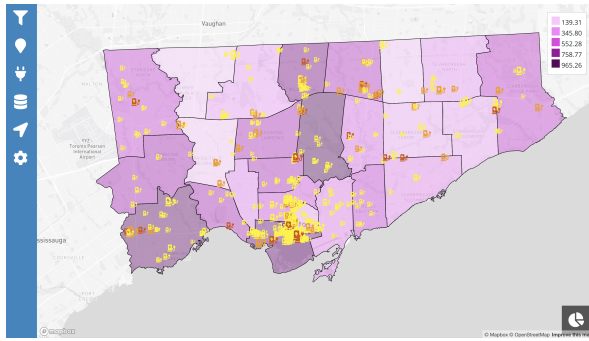
Results & Analysis

5.1 Passenger Vehicles

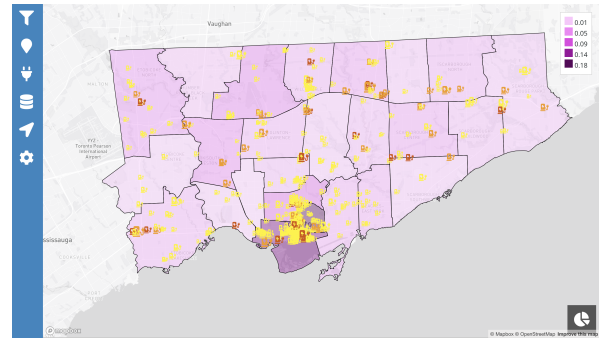
The results of this study are organized into two main sections: visualization and mapping of the provided data, and our optimization model results. First, we present various maps, visualized on Mapbox based on the gathered data, including the number of EVs and existing charging stations at the ward level to illustrate their distribution and the preferences of drivers for different charger types according to their trip purposes. Following this, we define the optimal number of charging stations per ward using our optimization model. Additionally, we conducted a sensitivity analysis to identify the parameters that significantly impact the determination of the optimal deployment cost.

5.1.1 Mapping Results

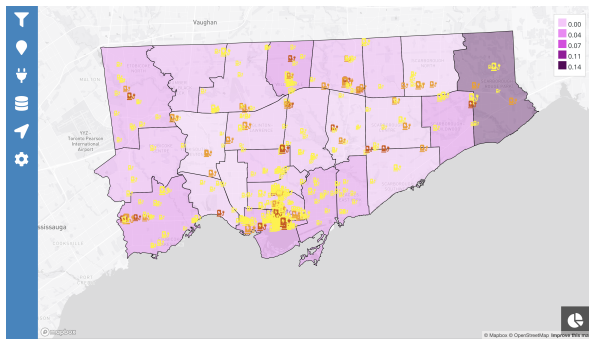
To develop a comprehensive understanding of the current configuration of EV charging stations, ownership distribution, and travel patterns, we created a series of shaded maps illustrating key metrics across Toronto’s wards. These visualizations are crucial for analyzing the spatial distribution and utilization of EV infrastructure, offering valuable insights into the effectiveness of the current network. By identifying areas where charging facilities are either underutilized or lacking, the maps play a vital role in highlighting gaps in the existing infrastructure. This analysis not only evaluates the present system but also serves as a foundation for future strategic planning, ensuring that EV infrastructure aligns with the



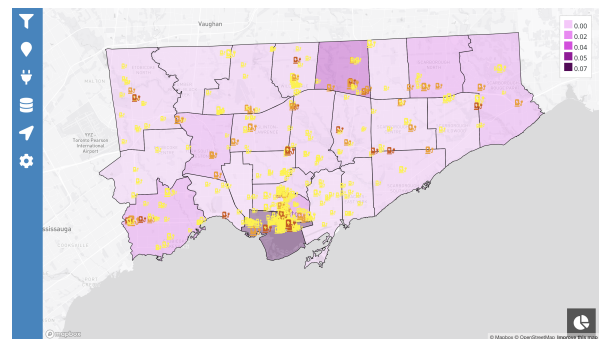
(a) Number of EVs



(b) Charging stations/Number of EVs



(c) Number of level 2 chargers/attraction of work trips to a ward



(d) Number of DC chargers/attraction of leisure trips to a Ward

Figure 5.1: Ward-level analysis with shading representing the selected ratio; lighter shades indicate lower ratios, while darker shades represent higher ratios.

city's evolving mobility needs.

Distribution of Electric Vehicles: Figure 5.1a illustrates the distribution of electric vehicles across Toronto's wards, with darker shades representing areas of higher EV concentration and lighter shades indicating regions with lower EV ownership. This map provides an overview of the spatial distribution of EVs, offering key insights into ownership patterns throughout the city. Serving as a baseline, the visualization enhances understanding of the geographical spread of electric vehicles and supports further analysis of infrastructure needs and future strategic planning.

Charging Station to EV Ratio: The following map (5.1b) illustrates the ratio of

charging stations to electric vehicles across Toronto's wards, with a noticeably higher ratio in the downtown core (Ward 10) compared to other areas. This difference is due to the downtown area functioning as a central hub that attracts commuters from various wards. The higher ratio suggests that the availability of charging stations in downtown Toronto is designed to serve both residents and commuters, improving accessibility for all EV users in the region.

Charger Types vs trip Purpose: The third visualization (5.1c) illustrates the ratio of Level 2 chargers to incoming work trips across Toronto's wards. While the downtown core does not exhibit the highest ratio, Ward 25 is highlighted as having a significantly higher concentration of Level 2 chargers despite a relatively low volume of incoming work trips. This finding suggests a potential overcapacity or a misalignment between the placement of Level 2 chargers and the actual demand for work-related EV charging in this area. Such discrepancies may indicate a need to reevaluate charger deployment strategies to better align with commuting patterns.

Conversely, Figure (5.1d) presents the ratio of Direct Current (DC) fast chargers to incoming leisure trips, revealing that the downtown core is well-supplied with fast chargers. This suggests that the placement of DC fast chargers is more aligned with the demand created by leisure activities, addressing the energy needs of electric vehicles during non-work-related travel.

5.1.2 Optimization Results and Discussion

The proposed optimization model seeks to identify the optimal number of Level 2 and DC fast chargers to minimize installation costs while meeting the energy needs of EVs and PHEVs. The model was applied to a base scenario, which assumed a 10% "garage orphan" ratio, indicating that 10% of residents in each ward lack access to home charging and rely on public

infrastructure. We considered an average work duration of 8 hours for Level 2 chargers (30 kW capacity) and a 2-hour limit for leisure trips using DC fast chargers (80 kW capacity). Charger availability preferences were weighted, with a value of 40 for DC fast chargers and 50 for Level 2 chargers. To account for cost differences, we estimated that the cost per outlet for DC chargers is four times higher than that of Level 2 chargers. Additionally, the model incorporated a battery consumption rate of 20 kWh per 100 km and an average daily commute distance of 23 km per EV. The optimization results for this base scenario are provided in Table 5.1.

Ward 10, which accommodates 6,030 work-related trips and is served by 469 existing Level 2 chargers and 28 DC fast chargers, has sufficient charging infrastructure and does not require further expansion. In contrast, Ward 21, a leading destination for leisure activities with 6,348 incoming trips, faces a significant need for additional DC fast chargers. The current infrastructure, consisting of 5 DC chargers, requires an increase of 66 units to meet demand, making it the ward with the highest need for DC charging capacity. However, due to the lower volume of work trips and the adequate number of existing Level 2 chargers, no additional Level 2 chargers are necessary in Ward 21.

Ward 3, with the highest total number of incoming trips at nearly 11,000, including 5,053 work-related trips and 5,670 leisure trips, showed a substantial increase in charging infrastructure. To meet this demand, 300 additional Level 2 chargers and 39 new DC fast chargers are needed. Combined with its existing 93 Level 2 chargers and 24 DC chargers, Ward 3 will have a total of 456 chargers, the largest network among all wards. In contrast, Wards 9, 16, 20, and 23 have significantly lower numbers of incoming trips. For example, Ward 9, with only 51 work-related trips and 2,664 leisure trips, does not require any new Level 2 chargers due to its sufficient existing infrastructure. Similarly, Ward 16, Ward 20, and Ward 23 require 15, 18, and 12 new DC fast chargers, respectively.

Ward ID	Incoming work trips for charge	Incoming leisure trips for charge	New Level 2	New DC	Existing Level 2	Existing DC
1	4,513	1,589	300	16	51	2
2	2,182	1,759	155	20	15	0
3	5,053	5,670	300	39	93	24
4	2,327	1,265	169	13	12	1
5	889	1,316	65	6	4	9
6	424	2,248	0	22	33	3
7	399	1,448	0	16	31	0
8	411	3,680	0	35	32	6
9	51	2,664	0	30	4	0
10	6,030	1,951	0	0	469	28
11	2,070	2,675	0	26	161	4
12	746	1,049	0	11	58	1
13	2,726	3,290	0	17	212	20
14	771	2,335	0	26	60	0
15	373	2,327	0	23	29	3
16	193	1,544	0	15	15	2
17	476	2,851	0	4	37	28
18	1,029	1,714	0	17	80	2
19	437	2,186	0	24	34	0
20	180	1,872	0	18	14	3
21	270	6,348	0	66	21	5
22	231	1,866	0	21	18	0
23	116	1,614	0	12	9	6
24	437	2,082	0	21	34	2
25	720	1,254	0	10	56	4

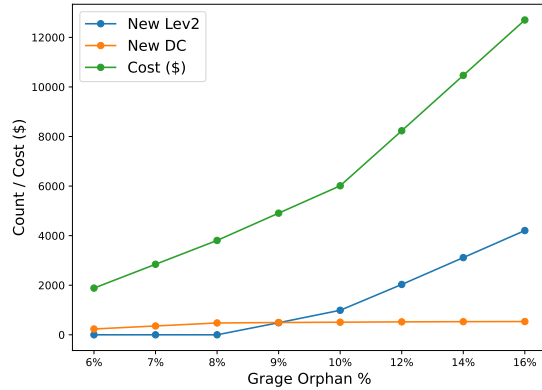
Table 5.1: Number of electric vehicle trips coming to a ward requiring charging, categorized by work and leisure purposes, and the deployment requirements for new Level 2 and DCFC

5.1.3 Sensitivity Analysis

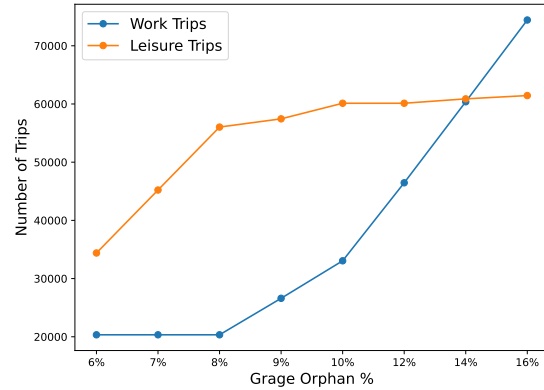
This section evaluates the impact of variations in individual parameters on the overall outcomes. The effect of each parameter is illustrated through two figures. The first figure shows the total number of newly required Level 2 and DC chargers across all wards, along with the associated costs. The second figure depicts the total number of work and leisure trips to all wards that lead to charging at the destination using existing and newly deployed chargers.

Garage orphans ratio: Figure 5.2 illustrates the impact of increasing garage orphan ratios on incoming work and leisure trips, leading to installing new chargers and associated costs. As shown in Figure 5.2a, there is a substantial increase in the demand for new Level 2 chargers as the garage orphan ratio rises from 6% to 16%, while the need for DC fast chargers grows at a slower pace. This trend indicates a preference for expanding Level 2 charging infrastructure among EV owners without home charging options, particularly when the ratio exceeds 8%, largely due to the lower installation costs of Level 2 chargers.

Figure 5.2b demonstrates a significant increase in both work and leisure trips as garage orphan ratios rise, with work trips experiencing a sharper increase. This growth is driven by the higher demand for accessible Level 2 chargers among EV owners without home charging options, resulting in a substantial rise in their numbers. In contrast, leisure trips grow more slowly due to the higher costs of installing new DC fast chargers, which moderates the increase in leisure trips as the ratio increases.



(a) Total number of outlets and charger cost vs. Garage orphans ratio



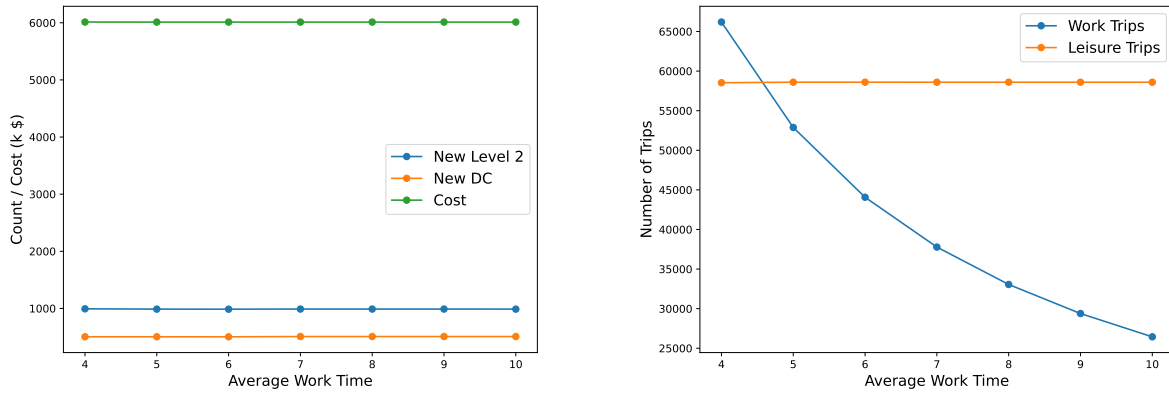
(b) Total incoming trips by purpose vs. Garage orphans ratio

Figure 5.2: Impact of garage orphan ratio on the total number of level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

Average work time: Figure 5.3 shows the impact of varying average work durations on the number of new charging outlets, associated costs, and incoming trips. As shown in

Figure 5.3a, the total number of new Level 2 and DC chargers, along with their costs, remains constant across different work durations. This suggests that charger demand is not influenced by variations in work time.

Figure 5.3b illustrates the relationship between incoming trips by purpose and work duration. As work times increase, the number of work trips decreases significantly, indicating greater utilization of Level 2 chargers during extended stays. In contrast, leisure trips remain constant, suggesting that leisure-related charging via DC fast chargers is unaffected by variations in work duration.



(a) Total number of outlets and charger cost vs. Average work time (b) Total incoming trips by purpose vs. Average work time

Figure 5.3: Impact of average work time on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

Average leisure time: Figure 5.4 examines the impact of average leisure time on charger needs and travel patterns. As leisure time increases, the need for new Level 2 chargers decreases, while the demand for DC fast chargers adjusts slightly, peaking at 3 hours. This pattern suggests a preference for DC charging during longer leisure periods. Installation costs decrease slightly, reflecting reduced demand for additional Level 2 chargers, and stabilize after 3 hours.

Figure 5.4b correlates incoming work and leisure trips with leisure time. As Leisure

trips also decline, albeit more gradually, suggesting that longer leisure durations reduce trip frequency, which in turn allows for greater utilization of DC fast chargers.

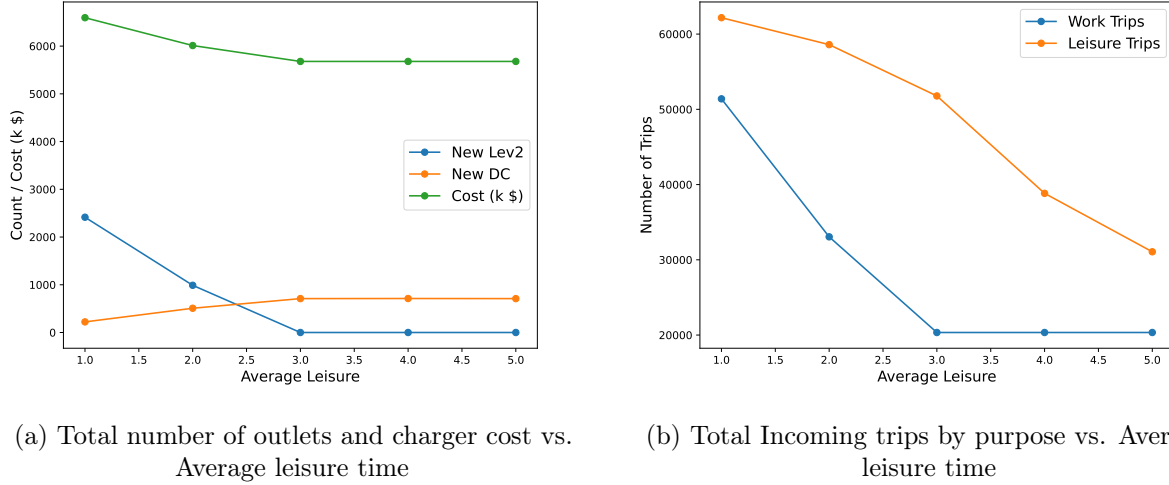
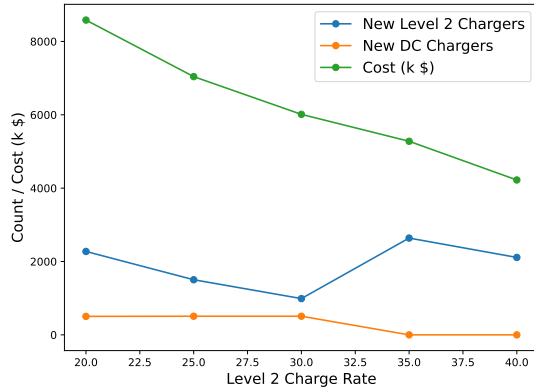


Figure 5.4: Impact of average leisure time on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

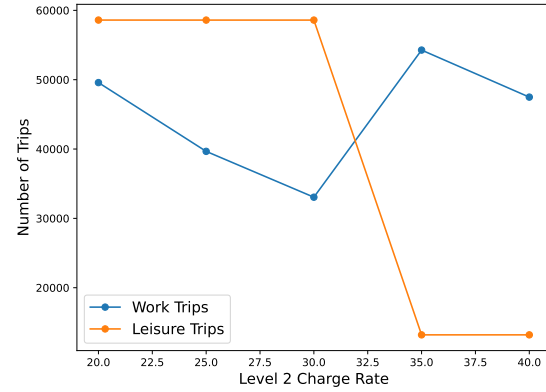
Level 2 charging power: Figure 5.5 illustrates the impact of Level 2 charging power on charger demand, costs, and incoming trips. As shown in Figure 5.5a, an increase in the charging power initially leads to a decrease in the demand for new Level 2 chargers, driven by their improved efficiency. However, demand slightly increases around 35 kW as some DC chargers are replaced by Level 2 units. Beyond this point, as the need for DC chargers drops to zero, the demand for Level 2 chargers also declines. Overall, installation costs decrease, reflecting cost savings from the transition to more efficient Level 2 chargers.

Figure 5.5b presents a steady decline in work trips as the charging power increases, indicating a reduced need for frequent charging. Leisure trips remain consistent up to 30 kW but then decline sharply, leveling off at zero beyond 35 kW. This suggests that charging needs for leisure trips are fully met earlier in the day, eliminating the requirement for further charging.

DC Charging Power: Figure 5.6 illustrates the impact of varying DC charging power



(a) Total number of outlets and charger cost vs. Level 2 charging power



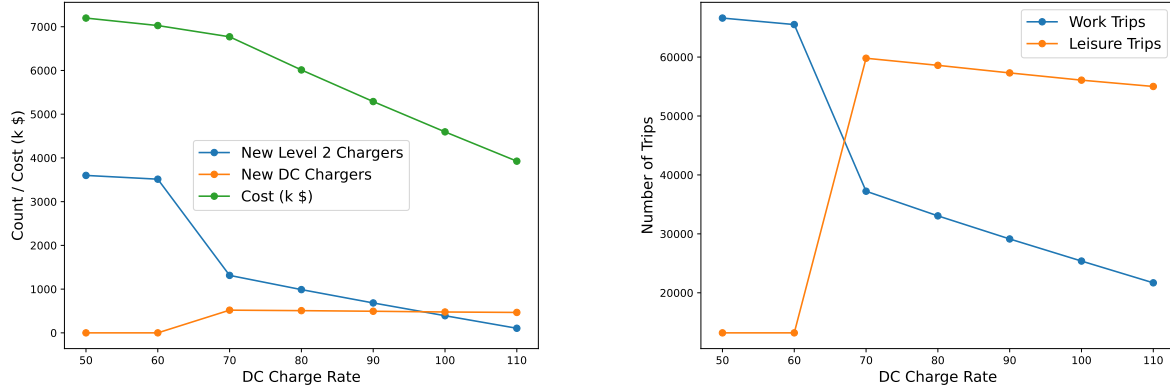
(b) Total incoming trips by purpose vs. level 2 charging power

Figure 5.5: Impact of level 2 charging power on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

on charger demand and trip patterns. As shown in Figure 5.6a, increasing the DC charge rate from 50 kW to 60 kW leads to a reduction in the number of new Level 2 chargers, as the enhanced efficiency of existing DC chargers reduces the need for additional Level 2 units. Between 60 kW and 70 kW, new DC chargers are introduced, accompanied by a sharp decline in the demand for Level 2 chargers, reflecting a shift toward more efficient charging options. Beyond 70 kW, the demand for DC chargers stabilizes, while the need for Level 2 chargers continues to decrease, indicating an optimal balance in the charging infrastructure, where further additions of DC chargers are no longer required.

Figure 5.6b analyzes the dynamics of work and leisure trips in relation to DC charging power. Initially, work trips are predominant, but as the power reaches the 60-70 kW range, there is a noticeable decline in work trips, while leisure trips begin to increase. This trend suggests that higher DC power more effectively meet the charging demands for leisure activities, driving a strategic shift in infrastructure usage. As the DC charging power continues to rise, leisure trips stabilize, whereas the number of work trips continues to decline.

Level 2 cost per outlet: The cost per outlet significantly impacts the number of new



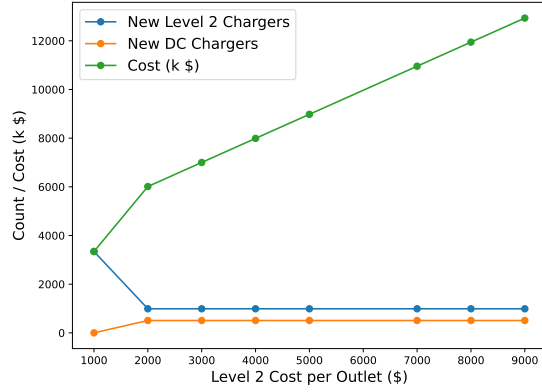
(a) Total number of outlets and charger cost vs. DC charging power (b) Total incoming trips by purpose vs. DC charging power

Figure 5.6: Impact of DC charging power on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

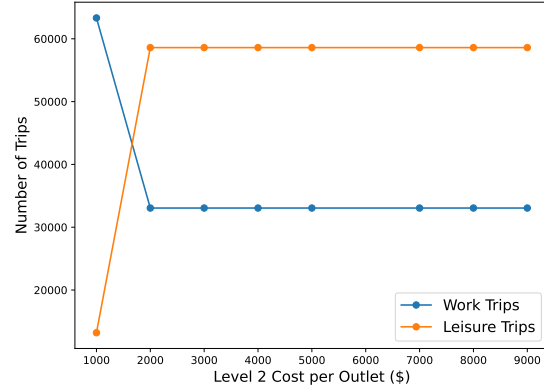
chargers and trip distribution, depicted in Figure 5.7. In Figure 5.7a, increasing the cost per Level 2 outlet from \$1,000 to \$2,000 markedly reduces the demand for new Level 2 chargers, while the need for new DC chargers increases due to their rapid charging capabilities. Beyond \$2,000, the deployment of new chargers levels off, indicating that higher costs do not further influence their numbers. The total cost rises consistently with the cost per outlet, showing the direct effect of unit cost increases on overall expenses.

Figure 5.7b examines how the cost per Level 2 outlet affects work and leisure trips. As costs increase, work trips significantly decline around the \$2,000 mark due to a shift towards using DC chargers and then stabilize at a reduced level. Meanwhile, leisure trips spike at the same cost point and then plateau, indicating a change in charging habits. This pattern suggests that beyond a certain cost threshold, the charging infrastructure becomes less feasible for work trips, leading to increased reliance on leisure trips for charging needs.

DC cost per outlet: Figures 5.8 displays the impact of varying DC charger outlet costs on the requirement for new chargers and associated costs. Figure 5.8a shows that as DC outlet costs rise from \$5,000 to \$10,000, the number of new Level 2 chargers remains



(a) Total number of outlets and charger cost vs. Level 2 cost



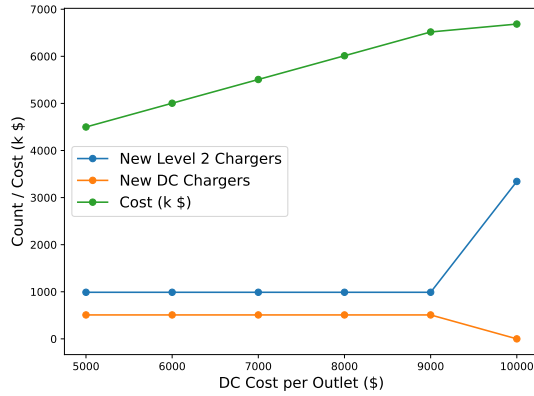
(b) Total incoming trips by purpose vs. Level 2 cost

Figure 5.7: Impact of Level 2 cost on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

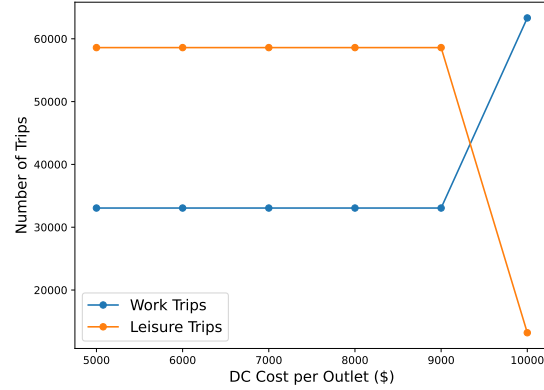
unchanged until \$9,000, then increases sharply. In contrast, the number of new DC chargers stays steady, declining slightly beyond \$9,000, indicating that while DC chargers are initially cost-effective due to their efficiency, a significant cost increase makes Level 2 chargers more economically viable. The total costs, shown by the green line, escalate with rising DC costs but the growth rate moderates after shifting to more Level 2 installations.

The second figure 5.8b explores how DC costs affect work and leisure trips. Work trips maintain stability until \$9,000, then surge, suggesting that higher DC costs enhance reliance on work trips for charging. Leisure trips initially hold steady but then diminish significantly, reflecting decreased leisure trip charging as DC costs increase.

Level 2 availability: Figure 5.9 explores the impact of Level 2 charger availability on new charger demand, trip volumes, and associated costs. As shown in Figure 5.9a, increasing availability reduces the demand for new Level 2 chargers up to a threshold of 40%, while the demand for new DC chargers remains constant. Beyond this threshold, a sharp rise in Level 2 charger installations indicates a transition away from DC chargers, eliminating the need for additional DC infrastructure. Figure 5.9b analyzes the effect of Level 2 charger



(a) Total number of outlets and charger cost vs. DC cost



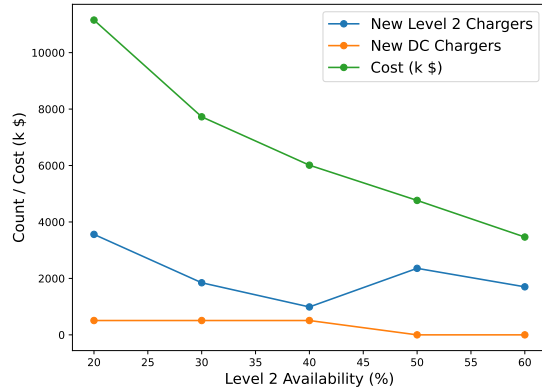
(b) Total incoming trips by purpose vs. DC cost

Figure 5.8: Impact of DC cost on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

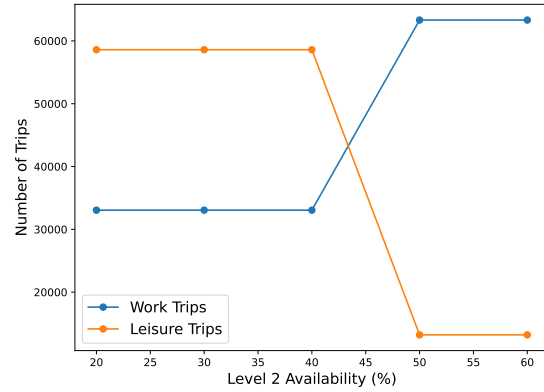
availability on work and leisure trips. The number of work trips remains stable until reaching 40% availability, after which it rises sharply, indicating increased reliance on work trips for charging as access to Level 2 chargers improves. In contrast, leisure trips remain steady initially but experience a sharp decline beyond the 40% threshold, reflecting reduced leisure charging as Level 2 charger availability increases.

DC availability: Figure 5.10 examines the impact of DC charger availability on the need for new chargers and their associated costs. In Figure 5.10a, as availability rises from 30% to 70%, the existing DC chargers initially meet energy demands, reducing the need for new DC chargers and lowering the requirement for Level 2 chargers by 40%. Beyond this threshold, the number of new DC chargers begins to increase, signaling a shift towards DC charging solutions. After 50% availability, the demand for Level 2 chargers stabilizes, while reliance on DC chargers slightly decreases. This suggests that the cost savings from higher DC availability are initially achieved but are eventually offset by increased infrastructure and maintenance costs as availability continues to rise

Figure 5.10b illustrates the relationship between DC charger availability and trip patterns.



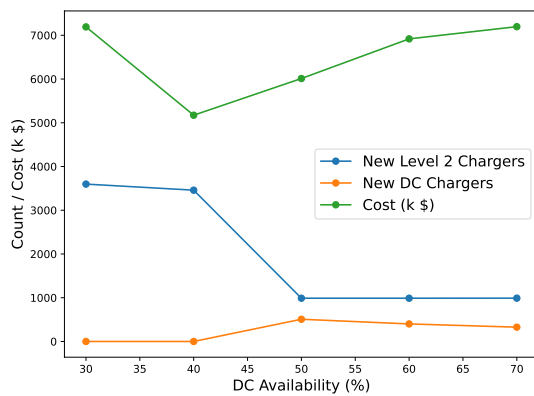
(a) Total number of outlets and charger cost vs. Level 2 availability



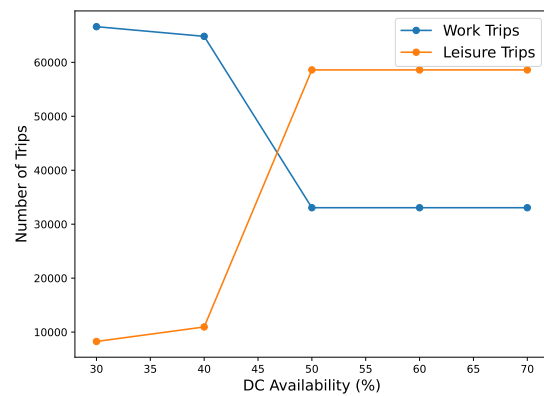
(b) Total incoming trips by purpose vs. Level 2 availability

Figure 5.9: Impact of level 2 availability on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

As DC availability increases, work trips show a slight decline, while leisure trips experience a modest rise, ultimately resulting in a significant shift toward the use of DC chargers primarily for leisure trips. This shift highlights the evolving charging behaviors as accessibility to DC chargers improves.



(a) Total number of outlets and charger cost vs. DC availability

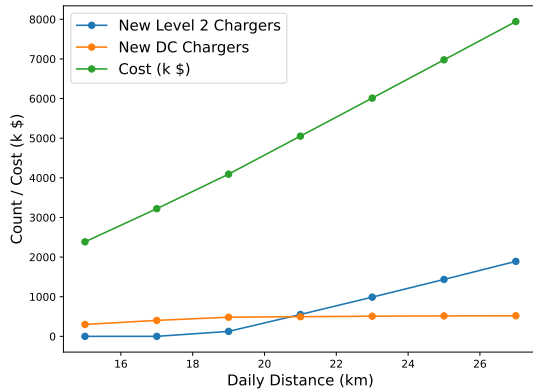


(b) Total incoming trips by purpose vs. DC availability

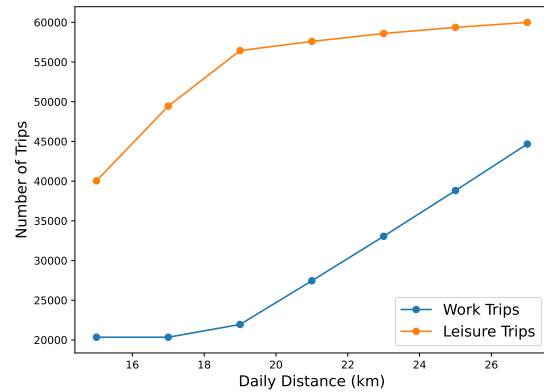
Figure 5.10: Impact of DC availability on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

Daily distance: Figure 5.11a illustrates the variations in the number of new Level 2 and DC chargers, along with the associated costs, as the daily distances traveled by EV drivers increase from 16 km to 28 km. Initially, there is no demand for Level 2 chargers, with only DC chargers being required. As the travel distance increases, the number of new Level 2 chargers rises steadily, highlighting the growing need for these chargers with longer distances. In contrast, the demand for new DC chargers sees a slight but consistent increase, remaining significantly lower than that of Level 2 chargers. The associated costs rise linearly with distance, reflecting the increased investment needed to expand the charging network.

Figure 5.11b shows that leisure trips begin at a high level and continue to rise steadily, reflecting consistent growth as travel distances increase. In contrast, work trips, starting from a lower base, experience a sharp increase between 16 km and 26 km, indicating a notable rise in work-related travel over longer distances. This trend then stabilizes as distances approach 28 km, suggesting that the demand for work-related charging reaches equilibrium at these distances.



(a) Total number of outlets and charger cost vs. distance



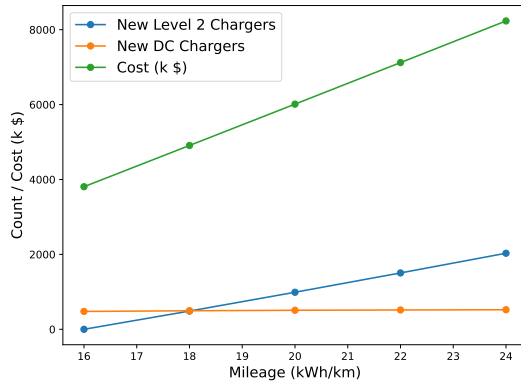
(b) Total Incoming Trips by Purpose vs. Distance

Figure 5.11: Impact of distance on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

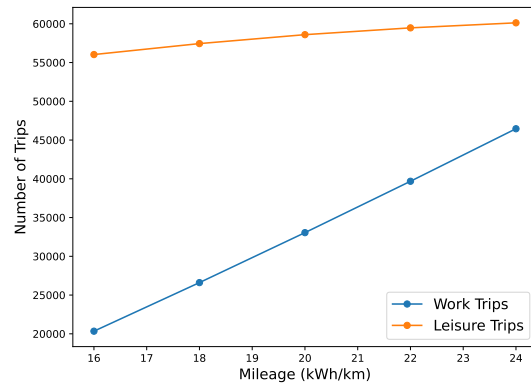
Mileage: Figure 5.12a illustrates how mileage affects the total number of new chargers

needed and the associated costs. As mileage increases from 16 kWh/km to 24 kWh/km, the demand for new Level 2 chargers rises significantly, while the need for DC chargers remains constant. This sharp increase in Level 2 chargers with higher mileage highlights the need for more frequent charging sessions due to greater energy consumption per kilometer, positioning Level 2 chargers as a more cost-effective solution. As a result, total installation costs rise proportionally, reflecting the expanded charger deployment required to accommodate increased mileage.

Figure 5.12b analyzes the relationship between mileage and trip volumes for work and leisure. As energy consumption per kilometer rises, leisure trips show a modest increase, while work trips experience a more significant surge. This trend suggests that higher energy consumption per kilometer leads to more frequent trips, as drivers may need to make additional stops to access conveniently located chargers. Consequently, this reflects an amplified demand for charging infrastructure to support the increased travel needs.



(a) Total number of outlets and charger cost vs. mileage

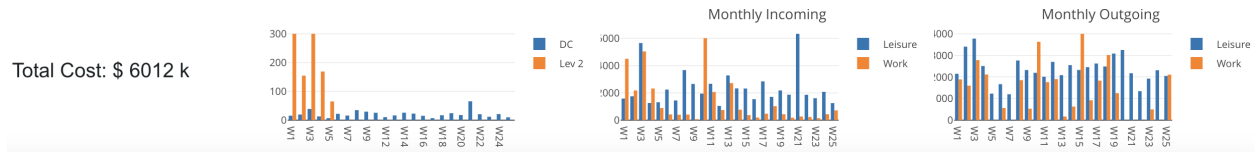


(b) Total incoming trips by purpose vs. mileage

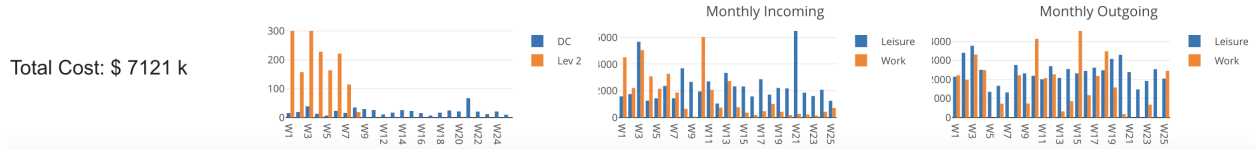
Figure 5.12: Impact of mileage on the total number of Level 2 and DC outlets (a) and total incoming trips to all wards by trip purpose: work and leisure (b)

Figure 5.13 presents the distribution of chargers across various wards and the dynamics of trips resulting in charging. This figure visualizes the outcomes under different scenarios

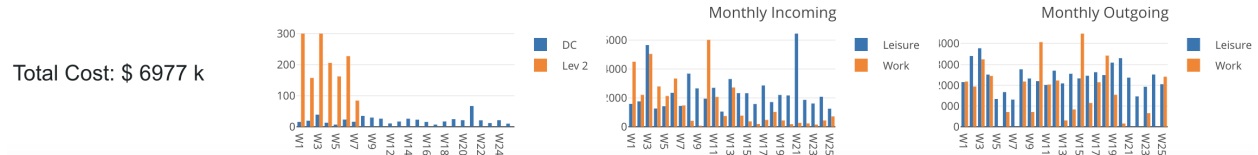
using key parameters such as garage orphan rates, daily commute distances, and charger availability. Each scenario demonstrates how changes in these variables impact the number and type of chargers required in each ward, alongside the associated changes in incoming and outgoing trips for work and leisure purposes. This approach allows for a comprehensive analysis of potential shifts in infrastructure needs and mobility patterns, highlighting the adaptability of the urban charging network to various demand fluctuations and planning strategies.



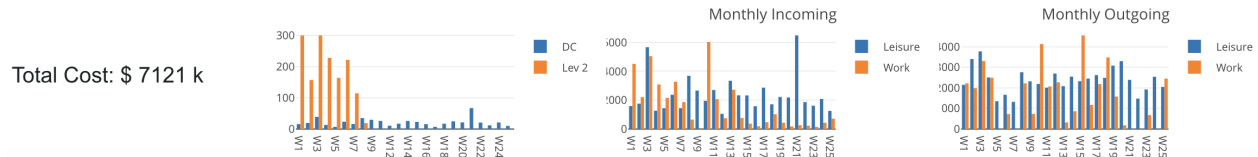
(a) Basic scenario



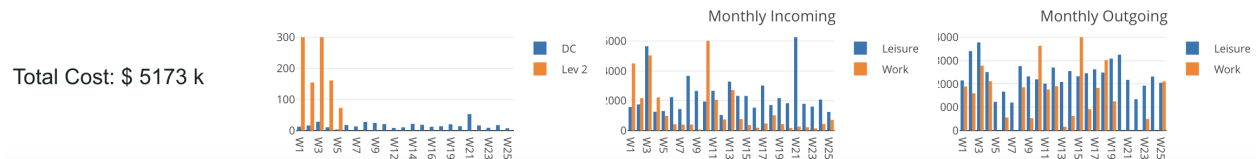
(b) 1% increase in garage orphan



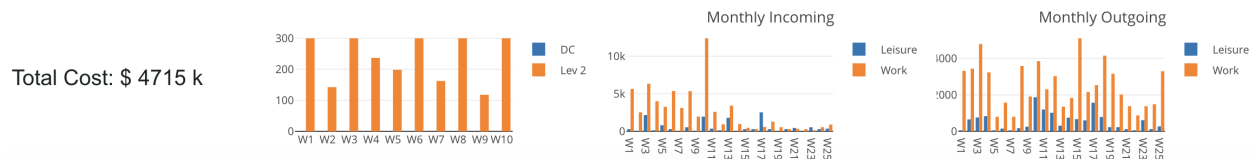
(c) 10% increase in average daily commute distance



(d) 10% increase in milage



(e) 10% increase in DC chargers availability



(f) 10% increase in Level 2 chargers availability

Figure 5.13: Optimization model results showing number of new chargers of each type required to be installed at each ward, incoming and outgoing trips with work and leisure purpose resulting in charging EVs

5.2 Medium and Heavy-Duty Electric Trucks

This section provides an in-depth analysis of the optimization results generated by the proposed algorithm. We begin with a detailed example of a trip from Quebec to Ontario, incorporating all relevant constraints and variables. Following this, we assess six distinct vehicle types, from Class 8 to Class 4, evaluating their performance based on specific properties and the energy supplied by existing and newly deployed chargers along the route. Lastly, we conduct a sensitivity analysis on key parameters, including battery capacity, consumption rate, and charger types, to examine their impact on the optimization outcomes.

5.2.1 Optimization Results and Discussion

The proposed model aims to identify optimal locations for integrating charging and resting facilities within truck rest areas along the highway 401-A20 corridor from Rivière-du-Loup, Quebec, to Windsor, Ontario. This corridor encompasses 58 strategic locations, including 21 charging stations and 37 rest stops, each within 10 km of the main route. Figure 5.19b illustrates the distribution and capacity of charging ports along this key highway corridor. Quebec offers an extensive charging infrastructure, with 19 Level 2 charging ports and 28 DC fast chargers along Highway A20, covering stations 1 through 26. At the same time, Ontario has 15 Level 2 chargers and 21 DC fast chargers deployed between stations 28 and 59. Spanning nearly 1,400 km, this corridor has notable gaps in charging availability, particularly between stations 29 and 39 and beyond station 45, highlighting a critical need to expand charging infrastructure in these areas to support reliable travel.

Beginning with a comprehensive example, the model was applied to the 2024 Volvo VNR Electric 6x2 Tractor, a Class 8 truck equipped with a 565 kWh battery capable of traveling 443 km per charge. With a consumption rate of 1.3 kWh/km and a DC fast charging capacity of 250 kW, the vehicle started its journey from Rivière-du-Loup fully charged at 565 kWh.

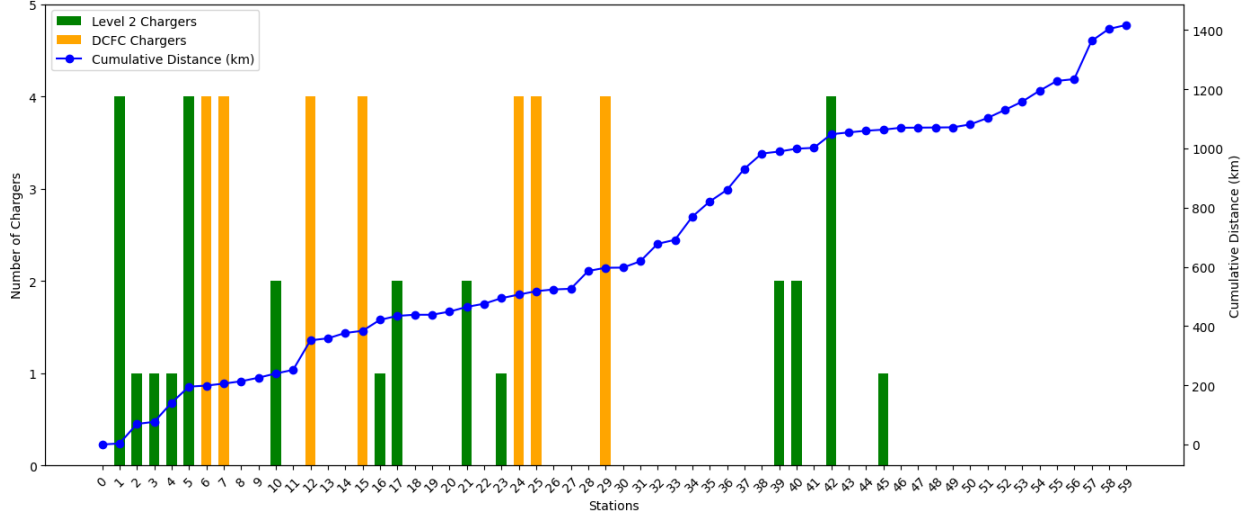


Figure 5.14: Distribution of charging station types, quantities per station, and cumulative distance

However, due to limited charging station availability along the route, the truck was unable to complete the trip, stopping at station 36 due to a state-of-charge violation as its SoC dropped below the 10% minimum buffer, reaching 56.5 kWh [136]. To address these constraints, the model identified stations 28, 34, and 46 as optimal locations for integrating 250 kW DC fast chargers with resting facilities, reducing the travel time to approximately 40 hours while maintaining compliant SoC and SoF levels.

As illustrated in Figure 5.15a, the truck began its journey from the origin with a fully charged battery and an initial state of fatigue set to zero. The first constraint violation occurred at station 16, where the state of charge dropped to 18.02 kWh, falling below the minimum allowable level. The model then backtracked to find the two nearest charging stations, selecting station 15 over station 12, as the next violation was anticipated further along the route at station 34. At station 15, a 1.76-hour charging session raised the SoC to its maximum level of 508 kWh, set at 90% of the battery's capacity. Moreover, since charging time contributes to on-duty hours, the SoF increases to the 6.8-hour threshold.

Passing subsequent stations without violation, the model detected a low SoC status at

station 34, directing the truck to station 28 for a 1.05-hour charging, increasing the SoC from 245.75 kWh to 508 kWh. Given the dual-purpose functionality of this facility, the SoF was also updated from 9.32 hours to 1.32 hours at this location. The next violation occurred at station 38 due to limited SoC, prompting the selection of station 37 over 29, as it provides both charging and resting facilities.

The final SoC violation occurred at station 57, where the model selected station 46 (over station 45) as the optimal stop, providing the driver an opportunity to rest and reduce SoF from 3.78 hours to zero hours. This stop also allowed the truck to recharge from 115.1 kWh to a full 508 kWh. According to Figure 5.15b, this scenario resulted in charging at four stations for a total of 5.33 hours and resting at three locations for a cumulative 15.3 hours, achieving a total travel time of 38.41 hours, the minimum travel time possible without breaching on-duty hours or encountering range anxiety.

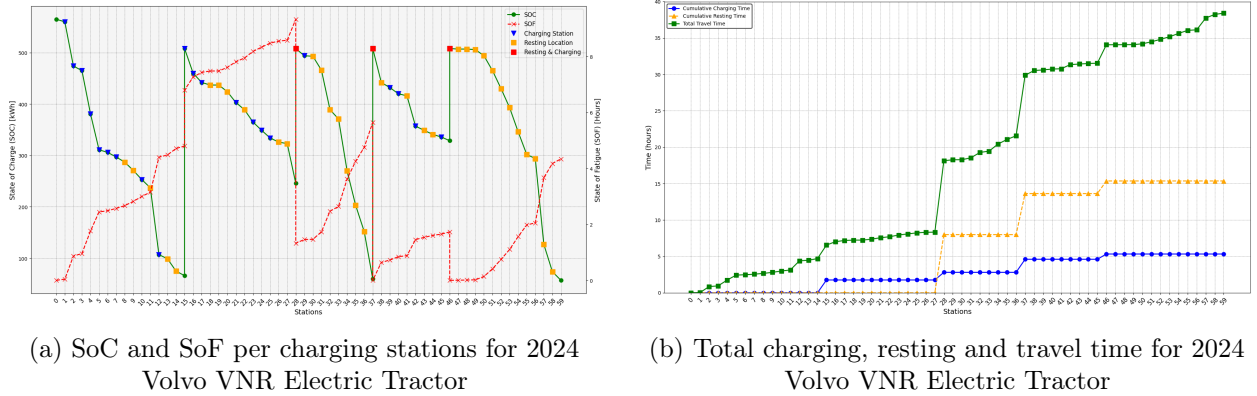


Figure 5.15: Impact of charging station availability in all of the resting areas on SoC and SoF (a) total resting, charging and travel time (b)

5.2.2 "No Charging Limit" Scenario

This approach evaluates a scenario where charging capabilities were added at all resting locations, analyzing the model's performance with ubiquitous charging availability for the

2024 Volvo VNR Electric 6x2 Tractor. The findings, presented in Figure 5.16, reveal that having charging stations at every rest stop does not inherently reduce travel time.

In this scenario, the truck reached its maximum charge capacity of 508 kWh at combined charging and resting facilities at stations 33, 41, and 56, where it also took rest breaks to achieve the minimum possible SoF at each stop. An additional charging session was completed at a dedicated charging facility at station 15, as illustrated in Figure 5.16a. By the journey's end, the truck's SoC was 270 kWh, with an SoF of 2.28 hours. The total travel time reached 41.15 hours, 2.15 hours longer than in the optimized scenario, with combined charging and resting times of 6.19 hours and 17.42 hours, respectively (Figure 5.17b).

According to the model, the truck simultaneously rests and charges until one of two conditions is met: either the SoC reaches its maximum within a 2-hour charging period (when the charging time exceeds the rest time required to reduce SoF to zero), or the rest time needed exceeds the maximum allowable charging time. In the latter case, the model prioritizes rest, allowing the SoF to reach its minimum by taking a full 8-hour rest. In the "no charging limit" scenario, the model utilizes the entire available resting capacity at stations to delay SoF violations. A comparison of Figure 5.15a and Figure 5.16a reveals that, in the former, the model selects stations to minimize total travel time, resulting in the lowest SoF and SoC at the destination. In contrast, the latter configuration includes longer breaks, leading to higher SoC and SoF levels upon arrival.

5.2.3 Truck Classes and Models Evaluation

In this section, we applied our approach to evaluate the electrification requirements along the 401-A20 highway corridor, focusing on six 2024 truck models. As outlined in Table 5.2, these models represent a range of medium- and heavy-duty classes that are either currently operational or in production. Our analysis aimed to identify optimal locations

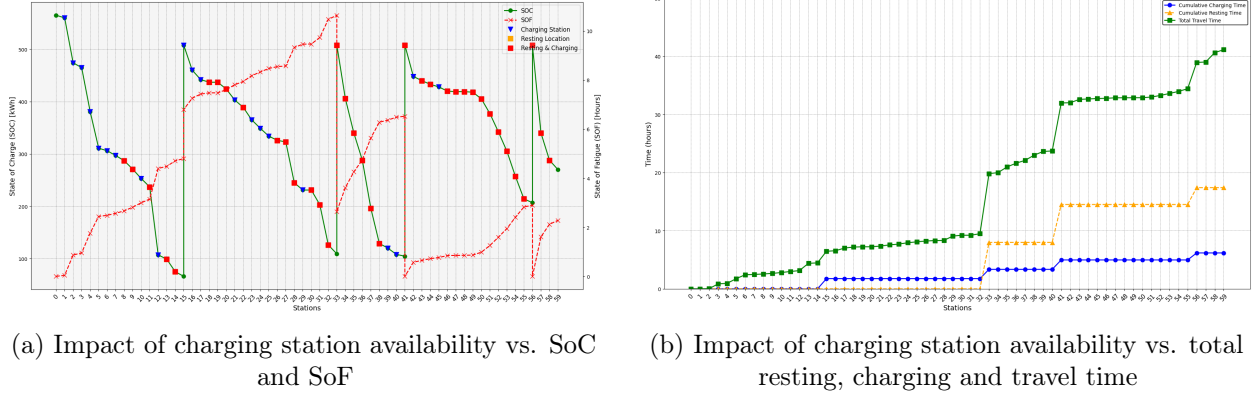


Figure 5.16: Impact of charging station availability in all of the resting areas on SoC and SoF (a) Total resting, charging and travel time (b)

for combined charging and resting facilities, prioritizing minimal travel time while adhering to on-duty regulations and state-of-charge requirements. By incorporating each truck's specifications, including battery size, energy consumption rate, and charger compatibility, the model identified optimal rest areas, need to be equipped with DCFC chargers. In the absence of detailed data on existing Level 2 and DCFC charger capacities along the corridor, we assumed that all chargers would meet each truck's charging requirements, as categorized in Table 5.2 by Level 2 and DCFC charging capacity. This strategy provides a comprehensive approach, ensuring the infrastructure meets the operational demands of various truck types [136].

As shown in Figure 5.17, distinct patterns emerge in the accumulation of travel, charging, and resting times across various medium- and heavy-duty electric truck models. The Volvo, Nikola, and Freightliner models, categorized as heavy-duty vehicles, exhibit similar behavior, while the LION, Workhorse, and EVT Motors models follow closer patterns as medium-duty trucks. Accordingly, we first analyze each truck class individually and then compare the performance of these two groups.

Heavy-duty Electric Truck: Heavy-duty electric trucks demonstrate comparable trends, with the Volvo VNR recording the longest total travel time at 38.4 hours, followed

Table 5.2: Comparison of heavy duty and medium duty electric trucks

	2024 Volvo VNR Electric 6x2 Tractor	2024 Nikola TRE Battery-Electric	2024 Freightliner eM2 Battery Electric	2024 Lion Electric Lion6 All-electric	2024 Workhorse W56	2024 EVT Motors Urban Truck
Class	Class 8	Class 8	Class 7	Class 6	Class 5, Class 6	Class 4
Type	On-Road Tractor	On-Road Tractor	Box Truck	Box Truck	Food Truck, Box Truck, Parcel Delivery	Box Truck
Electric Range	443 km/charge	531 km/charge	402 km/charge	351 km/charge	241 km/charge	274 km/charge
Battery Size	565 kWh	733 kWh	291 kWh	252 kWh	210 kWh	106 kWh
kWh/km	1.3 kWh/km	1.4 kWh/km	0.7 kWh/km	0.7 kWh/km	0.9 kWh/km	0.4 kWh/km
km/kWh	0.78 km/kWh	0.72 km/kWh	1.38 km/kWh	1.39 km/kWh	1.15 km/kWh	2.58 km/kWh
Level 2 Charge Capacity	0.0 kW	0 kW	0.0 kW	19.2 kW	20.0 kW	22.0 kW
DCFC Charge Capacity	250.0 kW	350.0 kW	270.0 kW	50.0 kW	100.0 kW	50.0 kW
Availability	Available	Pre-production	Available	Available	Production	Available
Total travel time	39.04 hours	34.02 hours	34.38 hours	58.74 hours	50.02 hours	47.66 hours

by the Freightliner and Nikola TRE at 35.9 and 34.02 hours, respectively. As illustrated in Figure 5.17a, the Nikola model makes its first stop at station 18 for simultaneous charging and resting earlier than other models, spending nearly 5 hours there. This makes it the first truck to begin resting but the last to require its initial charging session. This pattern is attributed to its higher battery capacity, allowing it to travel longer distances without needing to charge while benefiting from simultaneous charging and resting to reduce total travel time.

Additionally, Nikola's resting time is lower compared to the other models, as its high battery capacity minimizes the need for separate charging stops outside dual-purpose charge/rest areas. This efficiency helps avoid additional on-duty charging sessions required to reduce SoF by other trucks. In contrast, its total charging time falls between the two other models due to its higher battery consumption rate. However, the larger battery capacity allows it to plan charging stops further along the route, prioritizing locations where simultaneous charging and resting are possible, ultimately reducing its overall travel time.

The Freightliner has the second-lowest total travel time among the evaluated trucks. It also achieves the shortest total charging time, attributed to its smaller battery capacity and

lower energy consumption rate. The truck charged and rested at three dual-function stations simultaneously, with its first charging session occurring at a charging-only facility. With a charging capacity of 270 kW and a smaller battery size compared to other HDVs, the Freightliner achieves minimal charging duration. However, its total resting time is higher than that of other truck types. This outcome is due to the smaller battery capacity, which necessitates more frequent on-duty charging sessions, requiring the driver to take longer rest periods at dual-function facilities, thereby increasing overall resting time.

The Volvo VNR ranks as the third-lowest in total travel time among heavy-duty electric vehicles (HDEVs) but records the highest total charging and resting times compared to its counterparts. Despite having a battery capacity three times larger than the Freightliner, its DCFC charging capacity is lower, resulting in longer charging sessions and an increased number of stops for recharging, which collectively contribute to a higher total charging time. Additionally, the extended charging time, counted as on-duty hours, results in a higher total resting time compared to the Nikola TRE and equivalent to that of the Freightliner.

Medium-duty Electric Truck:

Medium-duty electric trucks exhibit comparable travel patterns, with the Lion Electric Class 6, Workhorse Class 5/6, and EVT Motors Class 4 featuring battery capacities of 252 kWh, 210 kWh, and 106 kWh, respectively. Their consumption rates are similarly aligned at 0.7 kWh/km, 0.9 kWh/km, and 0.4 kWh/km. The key distinction among these models lies in their charging capacities: the Workhorse supports DC fast charging at 100 kW, whereas the Lion Electric and EVT Motors models are limited to 50 kW. These medium-duty trucks also record the longest total travel times among all truck categories, with the Lion Electric Class 6 leading, followed by the Workhorse Class 5/6 and EVT Motors Class 4. Collectively, all three trucks align in their charging and resting patterns up to station 30, where they simultaneously charge and rest. Beyond this point, their behaviors diverge based on their specific properties.

The Lion Electric requires longer and more frequent charging stops due to its high battery capacity and slower charging power. In contrast, the EVT Motors Class 4 relies more on its battery efficiency, particularly between stations 37 and 51, as its lower consumption rate reduces the frequency of charging stops. Positioned between the Lion Electric and EVT Motors models, the Workhorse balances moderate charging and resting intervals. It benefits from shorter charging times, which allow for more efficient rest stops, ultimately resulting in a total resting time comparable to EVT Motors but lower than the Lion Electric Class 6.

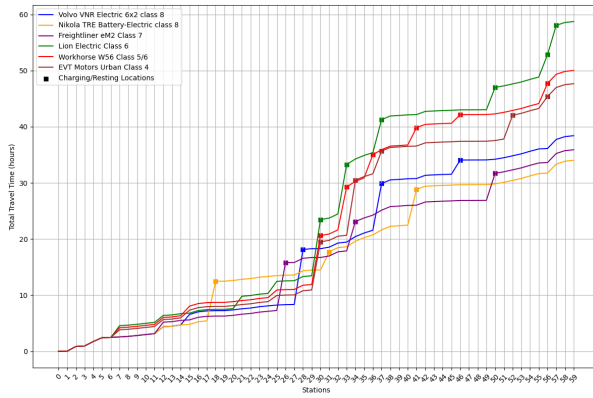
The Lion Electric Class 6 recorded the longest total travel time of 58.74 hours, marking the highest travel time among both medium- and heavy-duty electric trucks. Equipped with a 252 kWh battery and a consumption rate of 0.7 kWh/km, this truck required nine charging sessions, driven by its combination of the highest battery capacity and the lowest DCFC and Level 2 charging power among MDEVs (50 kW and 19.2 kW, respectively). This combination not only extended its charging time but also contributed to increased total resting time, as the truck's charging needs frequently coincided with on-duty hour limits requiring rest.

The Workhorse Class 5/6 ranks as the second highest in total travel time among medium-duty electric vehicles, reaching 50.02 hours. This truck made nine charging and six resting stops, utilizing six dual-function facilities where charging and resting occurred simultaneously. Equipped with a 210 kWh battery and a consumption rate of 0.9 kWh/km, the Workhorse Class 5/6 demonstrates a balance between battery capacity and energy efficiency. Despite its relatively higher charging capacities compared to other MDEVs (20 kW for Level 2 and 100 kW for DCFC), the Workhorse still ranks as the second highest in total charging time. This is attributed to its energy consumption rate and the frequency of required charging stops along the route.

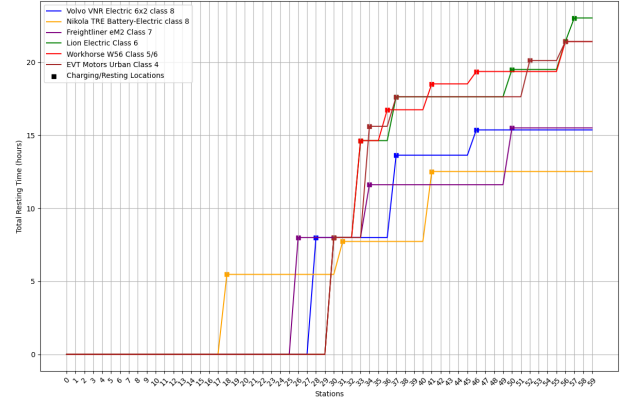
The EVT Motors Class 4 truck, equipped with a 106 kWh battery and a consumption rate of 0.4 kWh/km, demonstrates efficient performance. This truck can charge using Level 2 chargers with a capacity of 22 kW and DCFC chargers with a capacity of 50 kW. Throughout

its trip, the truck required 8 charging sessions, 5 of which occurred at dual-function facilities offering simultaneous charging and resting. This led to a total travel time of 47.66 hours, the lowest total charging and resting time among other MDEVs.

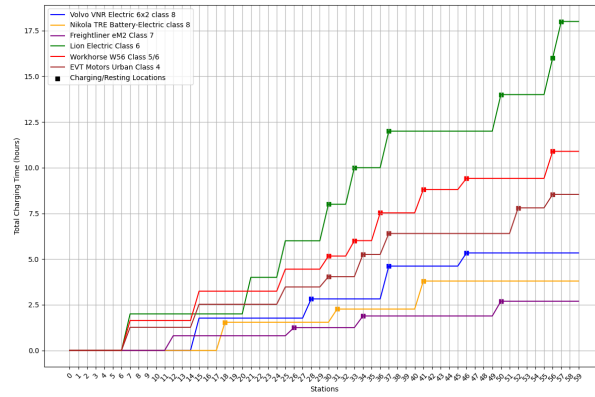
The reduced total charging time can be attributed to the compatibility between its smaller battery size and the charging capacities available. Additionally, the low consumption rate allows the truck to conserve its battery more effectively during the trip. All resting stops were strategically taken at dual-function stations, enhancing efficiency by balancing charging and resting limitations. This optimized approach ensured minimal downtime while adhering to operational constraints.



(a) Total travel time vs. vehicles types



(b) Total resting time vs. vehicles types



(c) Total charging time vs. vehicles types

Figure 5.17: Total charging, resting and travel time v.s different truck types

5.2.4 Sensitivity Analysis

Given the limited charging facilities along the highway corridor, we selected four rest locations to be equipped with chargers. Based on the Figure 5.17, stations 34, 37, 52, and 56 were identified as high-priority rest areas for charging infrastructure due to their significant demand. Consequently, we focused on these stations and conducted a sensitivity analysis on the involved factors to evaluate the sensitivity of input parameters.

High Charging Capacity Infrastructure

This section evaluates the model under the high charging capacity assumption for both existing and newly deployed stations. In this scenario, Level 2 chargers are capped at 20 kW, while DC fast chargers support capacities of up to 250 kW across all stations. The model's performance was analyzed across a range of battery capacities, spanning 200 kWh to 600 kWh for medium-duty vehicles with consumption rates between 0.4 and 0.7 kWh/km, and 450 kWh to 750 kWh for heavy-duty vehicles with higher consumption rates of 0.8 to 1.1 kWh/km. The findings are illustrated in Figure 5.16.

Medium-Duty Electric Trucks: Figure 5.18a illustrates total travel time across varying battery capacities for medium-duty electric trucks with different consumption rates. As shown, higher battery capacities result in decreased travel times, with the largest capacities yielding the shortest times. Trucks with a lower consumption rate of 0.4 kWh/km perform efficiently within a battery capacity range of 250 kWh to 500 kWh. For these truck types, as battery capacity increases, charging tends to shift to later stations. This shift leads to separate charging and resting intervals due to on-duty time limits, contributing to slightly longer travel times.

Figure 5.19b shows the distribution of charging stations used across various battery capacities and consumption rates. Lower consumption rates reduce the number of charging

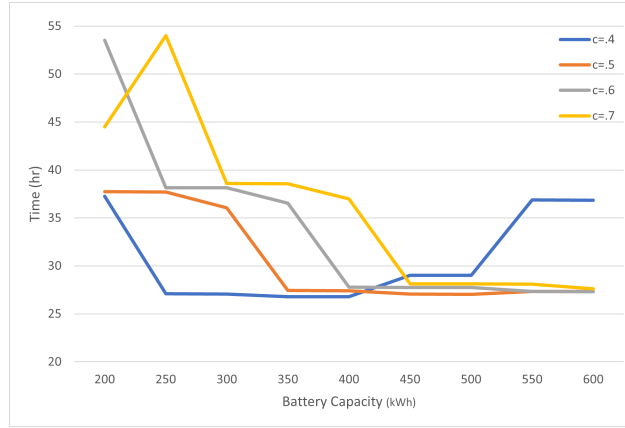
stops. Additionally, for all consumption rates, as battery capacity increases, the number of stations used generally decreases or stabilizes, indicating that larger capacities enable longer travel distances without frequent recharging. Stations 34 and 37 are frequently used for charging, supporting the choice of adding new stations in these rest areas. According to Figure 5.19c, the model also recommends resting at locations where charging and resting can occur simultaneously, minimizing the total travel time.

Heavy-Duty Electric Trucks: Figure 5.19 illustrates the performance of heavy-duty trucks with higher battery consumption rates, reflecting the increased energy demands due to their size and larger battery packs. Trucks with lower consumption rates (0.8-0.9 kWh/km) benefit consistently from higher battery capacities, while trucks with higher consumption rates (1.0 and 1.1 kWh/km) show a sharp improvement initially before reaching a point of diminishing returns. These jumps suggest that greater battery capacities enable trucks to rely on fewer, more distant charging stations, optimizing travel range.

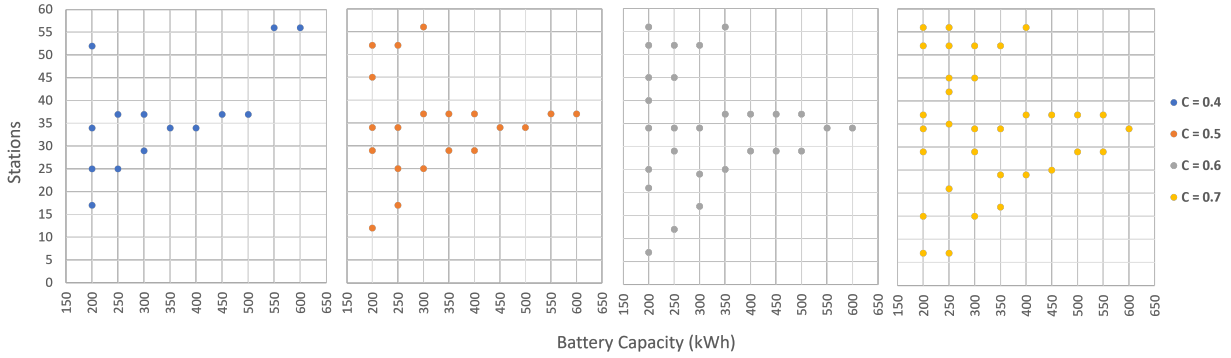
The 550-600 kWh battery capacity range appears to offer an optimal balance, reducing travel time and minimizing station stops across consumption rates. Higher consumption rates require more frequent use of charging stations, especially at lower capacities, while lower consumption rates allow for extended travel distances with fewer stops. This pattern emphasizes the importance of selecting suitable battery capacities to align with consumption needs, thereby maximizing efficiency for heavy-duty trucks on long-haul routes.

Low Charging Capacity Infrastructure

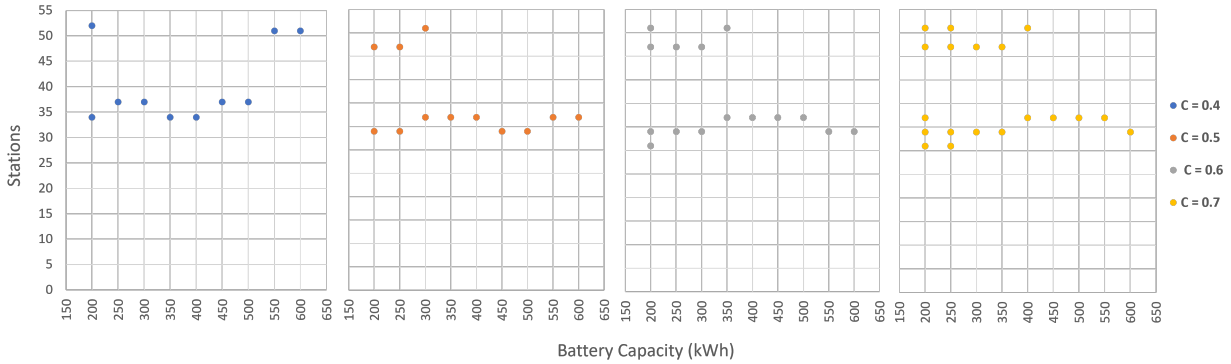
In this section, we evaluate a scenario with low charging capacity for both existing and newly deployed stations. Under this configuration, Level 2 chargers are limited to a capacity of 19.2 kW, while DC fast chargers are capped at 50 kW. We tracked the model's performance across various battery capacities. However, due to the lower charging capacities, more frequent charging stops are required, and the four designated resting areas proved insufficient for this scenario. Consequently, additional charging stations are necessary to meet the demands of



(a) Medium-duty trucks: total travel time across varying battery capacities and consumption rates



(b) Charging stations vs. battery capacity



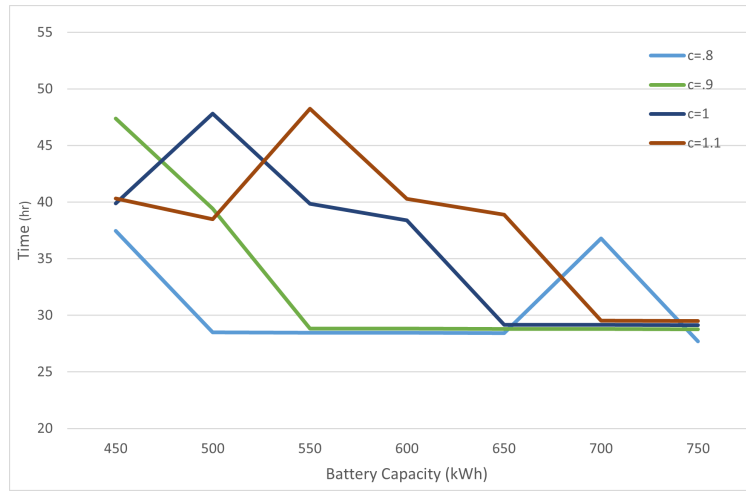
(c) Rest areas vs. battery capacity

Figure 5.18: Medium-duty electric truck's high capacity infrastructure: charging stations (a) and rest areas (b) utilized by each truck type across varying battery capacities and consumption rates

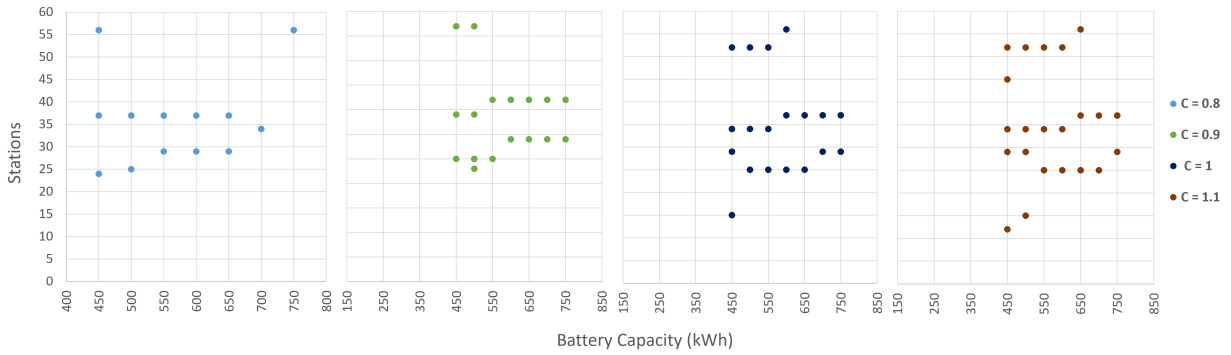
the route effectively.

5.3 Chapter Summary

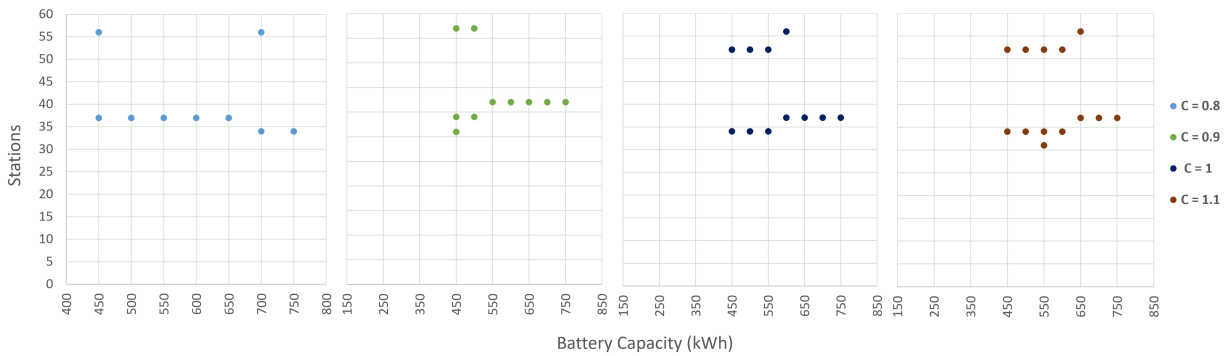
This chapter presents the findings of the optimization model developed for EV infrastructure deployment, focusing on both passenger vehicles and medium- to heavy-duty trucks. For passenger EVs, results indicate that a strategic mix of Level 2 and DC fast chargers across Toronto's wards effectively supports energy demands, particularly for garage orphans. In the context of medium- and heavy-duty trucks traveling the Highway 401-A20 corridor, findings highlight that larger battery capacities and strategically placed high-capacity charging stations reduce travel time and charging frequency, although lower-capacity scenarios require additional charging stops. The analysis underscores the importance of aligning charger types and station placement with vehicle consumption rates and battery capacities to achieve an optimal balance between travel time and charging needs across varying vehicle types and corridor demands.



(a) Heavy- duty trucks: total travel time across varying battery capacities and consumption rates



(b) Charging stations vs. battery capacity



(c) Rest areas vs. battery capacity

Figure 5.19: Heavy- duty electric truck's high capacity infrastructure: charging stations (a) and rest areas (b) utilized by each truck type across varying battery capacities and consumption rates

Chapter 6

Conclusion

6.1 Summary

The final chapter summarizes the research’s conclusions and contributions, acknowledges its limitations, and suggests areas for future work. It highlights the study’s impact on EV infrastructure research, particularly through the development of an optimization framework tailored to Ontario’s unique urban and intercity needs. Limitations such as data constraints and model assumptions are discussed, addressing factors that may affect the accuracy and scalability of the findings. Future work proposes enhancements to strengthen the study’s impact in advancing electrification, offering insights for refining EV infrastructure planning and supporting the broader transition to sustainable transportation.

6.2 Literature Contribution

This study presents a comprehensive framework for optimizing EV infrastructure planning in Ontario, aligning with Canada’s commitment to achieving net-zero greenhouse gas emissions by 2050. By addressing the needs of both light-duty and medium- to heavy-duty electric vehicles, this study provides tailored solutions for urban and rural regions, supporting EV growth in diverse environments. The framework offers a strategic approach to deploying EV charging stations in both densely populated urban centers and along essential transportation corridors. This approach not only supports current demands but also establishes a scalable

model adaptable to other regions aiming to transition toward sustainable transportation.

For light-duty vehicles, the study reveals a critical need to expand charging infrastructure, particularly as the number of "garage orphans"—drivers without home charging access—continues to rise. By analyzing work and leisure trips, which represent a large portion of urban travel, this research highlights the growing demand for both DC fast chargers and Level 2 chargers. Key areas in Toronto, including Etobicoke North, Etobicoke Centre, Etobicoke-Lakeshore, and Parkdale-High Park, are identified as high-priority locations where additional charging stations would greatly enhance accessibility and meet travel demands. Strategically deploying a variety of charger types within these wards would ensure efficient and widespread EV support across the city.

For medium- to heavy-duty vehicles, the findings underscore the importance of integrating charging and resting facilities, particularly for commercial trucks that rely on minimizing travel time to meet delivery schedules. The analysis indicates that the current charging infrastructure along the Highway 401-A20 corridor is inadequate to support these vehicles fully, thus requiring additional chargers to prevent range anxiety and ensure reliable operations. High-capacity DC fast chargers (250 kW) and Level 2 chargers at strategic locations, including stations 34, 37, 52, and 56, are recommended as essential deployments. These locations would accommodate various truck classes with differing battery capacities and charging needs, supporting efficient and uninterrupted long-haul travel.

Ultimately, this study serves as a foundational resource for policymakers and stakeholders to begin implementing an effective and efficient EV charging network across Ontario. By highlighting areas of need and recommending optimal station types and placements, this framework provides a practical pathway for Ontario's EV infrastructure expansion, setting the stage for a more sustainable transportation future and offering a model that can guide similar initiatives in other regions.

6.3 Research Limitations

One significant limitation of this study is the scarcity of detailed data, which impacted several aspects of the analysis:

Electric Vehicle Travel Patterns: To determine the number of trips taken by electric vehicles between Toronto’s wards, we utilized the Transportation Tomorrow Survey database. However, this database encompasses all vehicle types, not exclusively EVs. To address this, we estimated EV trip numbers by calculating the ratio of EVs to total vehicles within each ward and applying this ratio to the overall trip numbers for each ward, thus approximating the EV-specific travel patterns. Another key limitation is the reliance on the most recent TTS data, which dates back to 2016. While this dataset offers valuable insights into historical trip patterns, it does not account for the significant growth in EV ownership or shifts in travel behavior through 2023. To improve the study’s accuracy and align trip distribution data with 2023 EV ownership levels in each ward, future research will explore predictive methodologies. These approaches may include linear forecasting models or more advanced mathematical techniques to project EV trip patterns for 2023, using the 2016 data as a baseline.

Resting and charging locations: Data on charging and resting facilities was also limited. Specific details such as the charging capacity of Level 2 and DCFC were not included. To accommodate this gap, we modeled two scenarios: one assuming high charging capacities (20 kW for Level 2 and 250 kW for DCFC) and the other assuming lower capacities (19.7 kW for Level 2 and 50 kW for DCFC). Additionally, data did not specify truck rest areas or physical site characteristics (e.g., station size) that determine whether different truck sizes can access these facilities. Consequently, we assumed that trucks would not be able to rest at charging-only stations. Furthermore, as this study focuses on deploying charging stations within rest areas, the data limitations also extended to electricity capacity at these sites. In the absence of specific information, we assumed that all rest areas could support both high-

and low-capacity charging stations.

6.4 Future Work

This study can be further expanded by incorporating additional factors and methodologies to enhance the precision and applicability of its findings.

Future research on passenger electric vehicles would prioritize forecasting EV adoption trends for 2023 and beyond by leveraging historical EV ownership data and demographic insights from the Transportation Tomorrow Survey. Key factors such as age, race, income levels, and other influential parameters can provide a comprehensive understanding of EV growth and adoption trends. Additionally, exploring the feasibility of installing new chargers at public parking locations, including on-street parking and centralized parking hubs, would address accessibility gaps and improve the user experience. Furthermore, evaluating the capacity of the existing electricity grid is essential to ensure it can effectively support the growing demand for charging infrastructure and seamlessly accommodate the anticipated expansion of the EV market.

In the medium- and heavy-duty truck sections, several considerations could improve the precision of the evaluation. First, battery consumption variability could be addressed by accounting for variations in energy consumption due to weather conditions, altitude changes, and cargo weight, all of which significantly influence a truck's overall energy requirements. Second, station electricity capacity could be evaluated to determine whether existing charging stations can support a diverse range of trucks and whether they are equipped to accommodate varying sizes and energy needs. Third, station capacity and queue management could be integrated into the model to reflect more realistic scenarios by considering station-level service metrics, such as the number of trucks that can charge simultaneously and potential wait times. This would help evaluate service levels and prevent station overcrowding. Lastly, budget constraints could be introduced to the analysis, as this study currently assumes unlimited financial resources for deploying charging stations. Including financial limitations would

provide a more practical and nuanced perspective on deployment feasibility.

Evaluating corridor demand for electric truck traffic flow is another potential extension of this study. A comprehensive demand assessment could be undertaken to evaluate not only whether different truck models can complete their trips under existing charging and on-duty constraints but also to provide a more detailed understanding of electricity demand along the corridor. Also, incorporating traffic flow data would allow for more targeted placement of charging and resting locations, ensuring they meet the actual demand patterns within the corridor.

Future research could evaluate alternative zero-emission technologies—such as hydrogen fuel cells and biofuels—to determine which option best serves the Highway 401-A20 corridor’s energy and emissions needs. This comparative approach could lead to optimized, sustainable solutions for this major transportation route.

This approach could be extended to evaluate additional highway corridors, such as Highway 11, connecting Ottawa to Winnipeg, as well as other international highways linking the U.S. to Canada. Applying this model to various corridors would provide a broader understanding of infrastructure needs across major routes, facilitating a cohesive and comprehensive strategy for nationwide and cross-border electric vehicle support.

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Appendices

Table 6.1: Trip from origin wards to destinations with the "Market" trip purpose

Wards	Wards Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Etobicoke North	4448	642	630	33	252	157	260	438	0	28	23	63	53	0	0	0	32	88	0	0	16	0	0	0	0
2	Etobicoke Centre	522	4118	5069	180	596	64	26	253	35	77	118	16	167	56	10	0	30	0	0	0	0	15	0	0	0
3	Etobicoke-Lakeshore	175	861	9630	610	234	0	28	0	153	254	188	17	280	61	20	0	0	45	0	0	0	0	0	34	0
4	Parkdale-High Park	27	114	1567	2790	902	0	0	83	1397	281	788	32	278	81	0	0	0	10	13	0	0	0	0	0	0
5	York South-Weston	184	320	122	387	4373	586	966	986	667	115	189	151	215	0	15	7	13	0	30	0	71	26	41	0	0
6	York Centre	41	23	11	18	369	2576	738	903	36	80	15	0	74	0	28	37	81	494	0	0	35	0	0	0	0
7	Humber River-Black Creek	667	25	17	0	463	887	2725	505	53	16	55	0	151	0	69	0	28	112	0	0	0	0	0	0	0
8	Eglinton-Lawrence	20	0	17	0	497	1818	0	4451	286	37	227	229	163	55	680	171	242	176	25	0	117	0	0	0	0
9	Davenport	5	48	337	327	1096	155	0	150	3347	248	846	159	913	23	0	7	26	5	0	0	0	47	0	0	0
10	Spadina-Fort York	28	16	1058	124	60	19	0	143	760	2499	609	27	1338	286	174	23	0	75	15	21	8	12	0	22	0
11	University-Rosedale	0	0	100	0	50	40	5	404	673	1065	2565	287	936	41	394	72	0	0	6	0	69	0	0	0	0
12	Toronto-St. Paul's	0	0	58	52	228	362	0	1964	1087	141	1238	1976	485	132	772	149	193	57	19	0	86	0	0	0	0
13	Toronto Centre	0	11	134	18	0	0	0	175	161	899	991	110	3071	1051	90	0	30	72	87	11	41	0	0	0	0
14	Toronto-Danforth	0	0	88	16	71	0	0	45	109	273	357	46	985	4085	880	104	117	5	482	128	709	0	0	0	0
15	Don Valley West	0	0	7	0	0	181	13	750	14	14	172	271	217	178	3611	724	659	169	19	92	570	19	21	52	0
16	Don Valley East	0	0	28	0	0	54	0	210	49	51	83	24	215	123	519	2771	806	112	148	721	2135	106	10	16	0
17	Don Valley North	0	0	13	0	10	151	54	212	0	36	62	40	74	10	76	589	4842	641	70	153	761	924	26	5	0
18	Willowdale	30	0	0	0	0	1039	0	513	0	21	122	33	477	0	115	229	1899	3573	0	0	95	44	91	0	9
19	Beaches-East York	0	30	131	50	0	0	0	83	36	105	245	17	464	1302	274	22	166	0	4548	1172	1539	89	0	8	0
20	Scarborough South-west	0	0	0	0	6	10	0	24	0	48	92	11	130	295	29	214	33	67	1795	3572	3710	89	59	799	19
21	Scarborough Centre	0	0	18	0	0	35	0	28	0	43	16	46	85	73	57	137	109	74	46	974	5782	187	159	735	40
22	Scarborough-Agincourt	17	0	0	0	0	0	28	37	0	98	0	0	31	0	0	100	1165	51	20	31	2257	3707	399	30	0
23	Scarborough North	0	0	22	0	0	0	0	0	0	13	25	0	107	4	0	10	238	11	0	0	1226	821	3233	249	457
24	Scarborough-Guildwood	0	0	10	0	12	0	0	69	0	32	67	0	234	0	0	118	47	0	72	374	2489	86	348	4143	617
25	Scarborough-Rouge Park	0	0	0	0	0	0	12	0	16	29	0	0	108	0	0	18	67	0	30	69	1412	95	993	848	3039

Table 6.2: Destination wards with the "Work" trip purpose

Wards	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1 Etobicoke North	6155	714	1946	194	1389	1479	1936	807	198	1682	1522	380	1456	218	579	442	319	433	47	74	189	163	370	10	166
2 Etobicoke Centre	1698	2901	4261	696	832	818	485	772	437	3883	3034	711	2728	273	396	448	300	578	167	47	122	89	74	20	15
3 Etobicoke-Lakeshore	1556	1306	8039	1779	509	758	462	772	639	7511	4594	1217	4487	365	478	669	295	563	343	107	334	89	166	63	83
4 Parkdale-High Park	934	458	1691	3543	621	478	537	793	1028	10191	5717	1132	4882	667	521	593	394	344	64	174	150	80	54	345	57
5 York South-Weston	1818	678	1437	1212	3790	1839	1769	2419	1200	3986	3040	1091	2945	364	384	626	370	491	330	280	195	278	278	117	107
6 York Centre	545	140	702	377	1654	4581	2269	2660	442	2979	2542	1438	2476	190	934	664	646	2098	40	267	344	248	208	298	42
7 Humber River-Black Creek	2240	218	685	403	1107	2374	4758	1376	230	1653	1331	570	952	164	536	471	429	653	47	14	176	90	60	276	95
8 Eglinton-Lawrence	555	231	597	221	857	1816	814	4255	476	5604	4506	2330	3793	522	1331	1118	575	1224	249	207	471	148	297	63	51
9 Davenport	593	287	1362	1643	1094	833	637	1237	3535	9517	6660	1717	3487	742	704	617	321	617	187	65	174	159	128	132	161
10 Spadina-Fort York	343	287	1268	685	129	470	318	1285	590	25066	9200	1747	11859	1193	678	759	595	830	285	169	300	187	203	113	92
11 University-Rosedale	191	137	925	383	239	412	451	938	498	8475	11127	1663	6620	577	1104	465	118	589	238	366	238	68	36	168	57
12 Toronto-St. Paul's	383	132	724	302	418	1013	463	2124	922	9012	7341	4552	5553	511	1643	1096	645	1019	272	262	244	87	207	133	172
13 Toronto Centre	457	27	845	363	136	498	304	899	250	11518	8664	1523	10247	1188	872	801	571	892	493	523	223	92	174	89	63
14 Toronto-Danforth	165	154	690	289	319	344	217	858	358	8177	6270	1251	5927	4188	1479	1073	424	805	945	534	531	304	249	270	187
15 Don Valley West	293	31	434	164	101	860	374	1545	202	5465	3581	1977	3744	761	2738	1810	837	1309	206	401	533	220	218	219	109
16 Don Valley East	356	70	722	51	79	695	327	965	435	3652	2058	1096	2381	619	2345	3637	1431	772	640	576	1562	307	524	420	177
17 Don Valley North	435	32	408	115	333	832	375	1225	94	3539	2779	680	3192	372	1546	1628	3493	1741	295	562	1006	1055	969	250	259
18 18 Willowdale	583	134	416	56	239	1613	878	1133	206	6067	4701	1523	4226	308	928	1275	1728	4052	332	307	720	393	435	281	63
19 Beaches-East York	510	102	947	290	106	435	278	461	151	6892	4724	1242	5260	2042	980	1174	605	678	2676	1433	737	272	384	325	68
20 Scarborough Southwest	114	111	512	296	211	266	230	548	283	4008	2878	1002	3112	1563	969	1383	889	832	1843	3235	2851	625	917	936	222
21 Scarborough Centre	363	14	433	143	394	690	388	533	127	3371	2894	955	2491	623	1009	1852	1353	837	854	1633	5345	849	1530	1084	313
22 Scarborough-Agincourt	468	46	128	213	145	622	330	920	56	2642	1864	416	1505	317	643	1539	2000	1115	432	637	2041	2105	2107	494	270
23 Scarborough North	254	82	309	22	294	525	337	853	45	2448	999	319	1745	547	191	893	829	779	336	518	1851	1706	4208	990	763
24 Scarborough-Guildwood	281	97	181	108	21	408	373	347	99	2213	1934	458	1631	489	659	883	1226	550	443	1244	3757	552	2235	2391	1162
25 Scarborough-Rouge Park	242	47	398	33	53	458	382	462	175	2749	1756	533	2110	466	496	1168	773	815	479	1229	2948	973	2303	1335	1917