UNIVERSITY OF CALGARY

Mass EV adoption and Gas Station Closures: A Network-Based Analysis for Calgary

by

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ABSTRACT

In response to global environmental concerns and Canada's ambitious climate policies, a rapid transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs) is underway. Statistics Canada data show a strong shift toward electrified vehicles over the past five years. Compared to the same quarter in 2020, new registrations in Q2 2025 increased by approximately 375% for battery-electric vehicles, 441% for plug-in hybrids, and an even sharper 929% for conventional hybrids. This sustained multi-fold growth highlights the accelerating pace of electrification, even as internal combustion vehicles remain a significant share of the fleet during the transition period.

This research examines how this transition affects gasoline refueling accessibility for remaining ICE drivers in Calgary and other major Alberta cities. Using a quantitative geospatial methodology, the study integrates ArcGIS network analysis with Monte Carlo simulations of gasoline-station closures to measure additional detour distances required for refueling as EV adoption leads to gasoline demand reduction and station viability. The simulation framework quantifies how gasoline-station contraction increases refueling burden, using trip-weighted mean detour as the primary metric. It also identifies transition points using curve-based markers, indicating when the network shifts from robust to configuration-sensitive and eventually operationally inadequate.

Although the analysis focuses explicitly on refueling accessibility rather than traffic modeling, the findings carry broader implications for transportation planning. Increasing detours and localized refueling gaps can influence route choice, commuter reliability, and mobility equity for ICE users during the transition period. The results therefore support proactive planning for infrastructure adaptation as EV adoption accelerates.

By identifying when and where refueling accessibility becomes strained, this study provides a data-driven foundation to support municipal planners and policymakers. Its insights can guide strategic station retention, deployment of hybrid refueling sites, and coordinated expansion of EV charging infrastructure, contributing to a balanced, efficient, and equitable transition aligned with Canada's long-term decarbonization goals.

PREFACE

This dissertation is an original, unpublished, independent work by the author, Mohamad Essmayilkaboli.

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I wish to express my heartfelt gratitude to the following individuals for their invaluable support, exceptional backing, and steadfast belief in me throughout my academic journey.

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LIST OF ABBREVIATIONS

ICE – Internal Combustion Engine

ZEV – Zero-Emission Vehicle

EV – Electric Vehicle

BEV – Battery Electric Vehicle

PHEV – Plug-in Hybrid Electric Vehicle

GHG – Greenhouse Gas

CO_2-eq – Carbon Dioxide Equivalent

Mt – Megatonnes

LDV – Light-Duty Vehicle

GIS – Geographic Information System

OD – Origin–Destination

ΔD – Detour Distance

ΔD* – Allowable Detour Threshold

CSC – Critical Station Count

ASC – Acceleration Station Count

ConSC – Convenience Station Count

O→D – Direct Origin–Destination Network Distance

O→S – Origin–Station Distance

S→D – Station–Destination Distance

BCG – Boston Consulting Group

NRCan – Natural Resources Canada

CER – Canada Energy Regulator

ZEV SALES MANDATE – Canada's 100% ZEV Sales Regulation by 2035

CPU – Central Processing Unit

AAFC – Agriculture and Agri-Food Canada (used in fuel-blending references)

iZEV – Federal Incentives for Zero-Emission Vehicles Program

CHAPTER 1: INTRODUCTION

1-1 Background

Across Canada's major cities, a significant transition is reshaping the landscape of urban mobility. The transportation sector has become a central focus of national climate action as governments respond to rising environmental pressures and the need for cleaner, more resilient systems. Zero-emission vehicles (ZEVs), particularly battery electric vehicles, have emerged as a major pathway in reducing transportation-related emissions and modernizing mobility networks. In 2023, Canada's transportation sector accounted for 28% of national greenhouse gas emissions, 195 megatonnes of carbon dioxide equivalent (Mt CO_2-eq) out of 694, making it one of the largest emitting sectors nationally. Road transportation alone contributed approximately 63% of transport-sector emissions (122 of 195 Mt CO_2-eq), confirming that reducing emissions from on-road vehicles represents the primary pathway for decarbonizing the transportation sector. [3]

As electric vehicle (EV) adoption increases, cities stand to benefit from reduced pollution, lower noise levels, and improved long-term sustainability. These developments support Canada's broader transition toward a low-carbon future and highlight the importance of planning for how mobility systems will evolve during the shift from gasoline to electric propulsion. Canada's commitment to reducing emissions is more than just a policy, it is a reflection of its leadership in global climate initiatives. The ambitious targets include slashing emissions by 2035 and achieving net-zero status by 2050. To realize these goals, the federal government has rolled out comprehensive measures aimed at accelerating the transition to environmentally friendly vehicles. These measures include substantial incentives to make EVs more accessible to consumers, widespread investments in charging infrastructure, and stringent regulations that mandate a phased increase in the proportion of zero-emission light-duty vehicles sold. By 2035, all new light-duty vehicles must be zero-emission, with intermediate targets of 20% by 2026 and 60% by 2030. For medium and heavy-duty vehicles, the government aims for 35% of new sales to be zero-emission by 2030. [4]

These national strategies form a foundation for large-scale transportation electrification and set expectations for how the vehicle fleet will evolve over the coming decades.

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Also, the 2030 EV Action Plan developed by Electric Mobility Canada highlights a suite of strategic priorities to accelerate electric mobility in Canada. These priorities include enhancing the affordability of electric vehicles for consumers, advancing the electrification of passenger and fleet vehicles, expanding national EV charging infrastructure deployment, and implementing coordinated national strategies to improve zero-emission vehicle availability. The plan also emphasizes domestic electric vehicle job creation and manufacturing capacity and calls for federal leadership to convene stakeholders and drive policy coherence, illustrating an aggregated consensus across industry and government to address both market barriers and infrastructure readiness for an electrified transportation future. [49]

The transition to EVs also brings challenges that require coordinated planning. Expanding charging infrastructure, upgrading electrical systems, and integrating renewable energy sources all demand long-term investment and cross-sector collaboration. These challenges demonstrate that electrification is not only technological but also social and institutional, involving multiple actors and systems.

While these initiatives signify an optimistic outlook, the practical implementation of such measures requires navigating a web of challenges. Electrifying the transportation sector involves addressing infrastructure bottlenecks, such as the availability of charging stations and the capacity of the electrical grid to accommodate increased demand. The widespread adoption of EVs will demand significant investments in renewable energy generation to ensure that the environmental benefits of these vehicles are fully realized. Additionally, urban planners must consider the spatial and operational integration of charging stations into densely populated areas, balancing accessibility, convenience, and urban aesthetics.

The aforementioned, underscore the dynamic and complex nature of urban systems in responding to climate pressures, emphasizing the need for a profound re-evaluation of how cities are planned and developed. It stresses that effectively addressing climate change involves more than just technological solutions, it requires an integrated, proactive strategy that acknowledges the interconnectedness of social, ecological, and technological systems. This multifaceted challenge calls for a multidisciplinary approach, one that leverages the full spectrum of urban complexity and involves diverse actors in identifying and implementing a wide range of adaptive measures. [5] At the same time, EV adoption changes everyday mobility behavior. As recharging routines replace traditional refueling habits, public understanding and supportive infrastructure become essential to ensure smooth adaptation.

Because vehicle turnover is gradual, internal combustion engine (ICE) vehicles will remain common throughout the coming decades. This creates a prolonged dual-fuel period in which gasoline and electric vehicles coexist. As gasoline demand declines, fuel stations may close or consolidate, reshaping accessibility for ICE drivers. These emerging patterns motivate the central focus of this thesis: evaluating how declining gasoline station availability affects refueling accessibility for ICE drivers in Calgary.

This research analyzes these dynamics through quantitative geospatial modeling, employing ArcGIS Pro network analysis and Monte Carlo simulation of random gasoline-station closures to measure refueling detours and accessibility impacts. The findings provide evidence to support planning and policy decisions during Canada’s transition to an electrified transportation system.

1.2 Emerging Challenges Due to Mass EV Adoption

As the transition toward electric vehicles accelerates, a set of emerging system-level challenges begins to surface alongside well-studied issues such as charging deployment and vehicle affordability. Beyond the immediate technological and regulatory considerations, mass EV adoption can induce broader effects across urban mobility networks. One notable impact is the gradual decline in gasoline demand, which reduces the economic viability of traditional fuel stations and can lead to accelerated closures. For the remaining internal combustion engine users, these closures may translate into uneven refueling accessibility, extended detours, and localized gaps in service.

Such structural changes in fuel availability can indirectly influence mobility behavior and the functioning of urban travel systems. Reduced refueling convenience may alter route choices or shift travel routines, and in some contexts can interact with existing spatial patterns in ways that contribute to localized traffic congestions and disturbance. These effects are not the central analytical focus of this thesis, but they represent plausible secondary consequences of widespread electrification and illustrate why understanding the evolution of the gasoline station network remains important.

Taken together, these emerging considerations highlight that the EV transition extends beyond vehicle technology. It interacts with established infrastructures, user habits, and accessibility constraints, underscoring the need for proactive planning to support a smooth and balanced transition for all road users during the long period in which ICE and EV platforms will coexist.

Figure 1 Emerging Challenges Due to Mass EV Adoption.

1.2 Research and Objectives

This research aims to evaluate how Alberta's major cities will be affected by declining gasoline station availability during the transition from ICE vehicles to EVs. As EV adoption increases and gasoline demand decreases, traditional fuel stations may close at accelerated rates. Understanding how these closures influence refueling accessibility for remaining ICE users forms the central focus of this study.

The primary objective of this research is to quantify the additional detour burdens created by gasoline station closures, expressed through network-based metrics such as detour distance. Using geospatial analysis and Monte Carlo simulation, the study identifies how progressive station reductions reshape refueling patterns, affect accessibility across the network, and reveal structural vulnerabilities in the urban fuel network.

A secondary objective is to interpret how these detour-based impacts relate to broader urban considerations. Although this thesis does not model the traffic flow or system-wide behavior, changes in refueling accessibility can influence route choice and may interact with existing mobility patterns. Evaluating these effects helps situate the findings within the wider context of Alberta's long-term transportation transition.

To achieve these objectives, the research employs geographic information systems (GIS) for spatial processing, route-distance analysis, and visualization of network degradation across closure scenarios. The methodology is informed by peer-reviewed literature, government reports, and international experiences in EV adoption, providing a strong conceptual foundation for interpreting the results. The outcomes contribute practical insights for policymakers and urban planners by clarifying when and how the gasoline network becomes strained, and what implications this holds for managing a smooth, equitable transition during the coexistence of ICE and EV vehicles.

1.3 The Multifaceted Process

The transition from internal combustion engine vehicles to electric vehicles is a multifaceted process that interacts with many aspects of urban life. Although this study focuses specifically on the evolution of gasoline refueling accessibility during this transition, the broader context in which these changes occur remains important for interpreting the results. Declining gasoline demand, shifts in refueling behavior, and the long-term coexistence of ICE and EV vehicles all take place within complex urban systems that include land-use patterns, mobility routines, infrastructure networks, and policy environments.

Understanding these interconnected dimensions helps situate the refueling accessibility findings within a wider urban transition. While this thesis does not evaluate energy grid performance, urban fabric integration, or system-wide resilience, these elements form part of the broader landscape in which refueling networks evolve. The coexistence of emerging EV charging infrastructure and a contracting gasoline station network highlights a critical period in which accessibility, convenience, and continuity of service must be managed carefully.

Through this lens, the research contributes to ongoing discussions about sustainable mobility by clarifying one essential component of the transition: how gasoline station availability declines and how that decline influences detour burdens for remaining ICE users. This understanding provides valuable insight for policymakers and planners responsible for managing the long transition period in which traditional and electric refueling systems operate in parallel.

1.4 Thesis Organization

This thesis is structured into five chapters, each contributing to a focused examination of how the transition from ICE vehicles to EVs affects the gasoline refueling network in Calgary. The emphasis of the thesis is on quantifying accessibility changes for remaining ICE users as gasoline stations decline during the transition.

Chapter 1 introduces the research context, motivation, and objectives. It highlights the central issue of declining gasoline demand as EV adoption accelerates, leading to reduced economic viability and closures of gas stations. The chapter establishes the importance of understanding how these closures affect refueling accessibility, detour distances, and the overall functionality of the existing fuel network during the long coexistence of ICE and EV vehicles.

Chapter 2 reviews relevant literature on EV adoption, declining fuel infrastructure, and urban mobility transitions. It examines how fuel-network contraction intersects with accessibility, infrastructure planning, and user behavior, and identifies gaps in current research regarding quantitative assessment of detour burdens and network degradation caused by gas station closures.

Chapter 3 presents the model and methodology used to evaluate the effects of progressive gas station closures. It details the data sources, GIS pre-processing steps, ArcGIS network analysis tools, and Monte Carlo simulation framework used to compute detour distance and related network-level metrics. The chapter also outlines how closure sequences are generated and how detour impacts are aggregated and interpreted.

Chapter 4 applies the methodology to a case study of Calgary. It describes the data preparation process, route-event structure, and implementation of the Monte Carlo analysis for real-world station networks. The chapter reports key findings, including changes in average detour distance, distribution of refueling burdens, identification of critical stations, and patterns of network degradation as station availability declines. These results offer practical insights for planners and policymakers responsible for managing the transition period.

Chapter 5 summarizes the main findings and contributions of the research. It discusses implications for urban planning and the management of gasoline infrastructure during the shift toward electrification. The chapter concludes with limitations of the analysis and recommendations for future research, including potential integration with behavioral modeling, EV charging dynamics, and broader urban-systems analysis.

CHAPTER 2: LITERATURE REVIEW

2.1 Background and Problem Statement

2.1.1 EV Adoption and Declining Gasoline Demand

The increasing adoption of electric vehicles (EVs) is reducing demand for traditional gasoline stations, creating emerging infrastructure challenges in urban areas. As fuel sales decline, gasoline stations may close in a largely uncoordinated market-driven manner, reducing local refueling availability for remaining internal combustion engine (ICE) users. These closures can lead to longer refueling detours, uneven accessibility across neighborhoods, and localized operational pressure during the extended dual-fuel transition period.

2.1.2 Policy Drivers and National EV Objectives

In alignment with its objective to reach net zero greenhouse gas (GHG) emissions by the year 2050, the Canadian government has established a compulsory objective to attain a 100% zero-emission benchmark in new light-duty vehicle (LDV) sales by 2035. The realization of this ambitious goal calls for a collaborative effort encompassing federal, municipal, and provincial authorities, energy providers, the automobile sector, and various private entities. The Federal government has been instrumental in expediting the shift to zero-emission vehicles (ZEVs) through initiatives that enhance public awareness, provide purchase incentives, and bolster the EV charging framework.

2.1.3 Expansion of EV Charging Infrastructure

Since 2016, Natural Resources Canada has been instrumental in the installation of numerous EV charging stations nationwide. Although market dynamics are expected to shape the future charging infrastructure, the complexity of charging business models suggests a need for continued cooperative engagement among all stakeholders, including government bodies, energy services, and the private sector.

2.1.4 Research Gap: Implications of a Contracting Gasoline Network

Despite multiple government and academic efforts to understand Canada's EV charging infrastructure requirements, far less attention has been given to the implications of a contracting gasoline network during the long dual-fuel transition period in which EV infrastructure expands while gasoline stations disappear. This transition raises fundamental questions of network adequacy and resilience: How rapidly can gasoline stations close before refueling accessibility degrades into localized “refueling deserts”? At what point does the detour burden shift from incremental increases to nonlinear escalation? These concerns also carry equity implications, as increased detour distances are unlikely to be distributed uniformly across urban areas, potentially imposing disproportionate burdens on peripheral, low-density, or time-constrained travelers who remain dependent on ICE vehicles.

2.1.5 Spatial Vulnerability and System-Level Performance

Beyond average effects, the variability and spatial concentration of refueling burdens are critical. Uncoordinated closures may amplify detour volatility and create vulnerability around specific stations and corridors whose loss has outsized consequences. Addressing these gaps requires a system-level evaluation that links EV-driven closure trajectories to measurable refueling burdens and to critical thresholds in network performance.

2.1.6 Study Approach and Relevance to Calgary

Accordingly, this study uses network-based detour metrics and Monte Carlo simulations to quantify refueling burden across milestone closure levels, identify key transition points (ASC, ConSC, and CSC relative to ΔD^*), and rank stations by aggregated marginal detour impact. This provides a quantitative basis for assessing how refueling accessibility in Calgary deteriorates as the gasoline network contracts.

Figures 2 and 3 illustrate Calgary’s existing gasoline station distribution and road network, highlighting the historically dense network that has enabled low-detour refueling of nearly 200 meters and helps illustrate why future gas-station closures may create accessibility gaps.

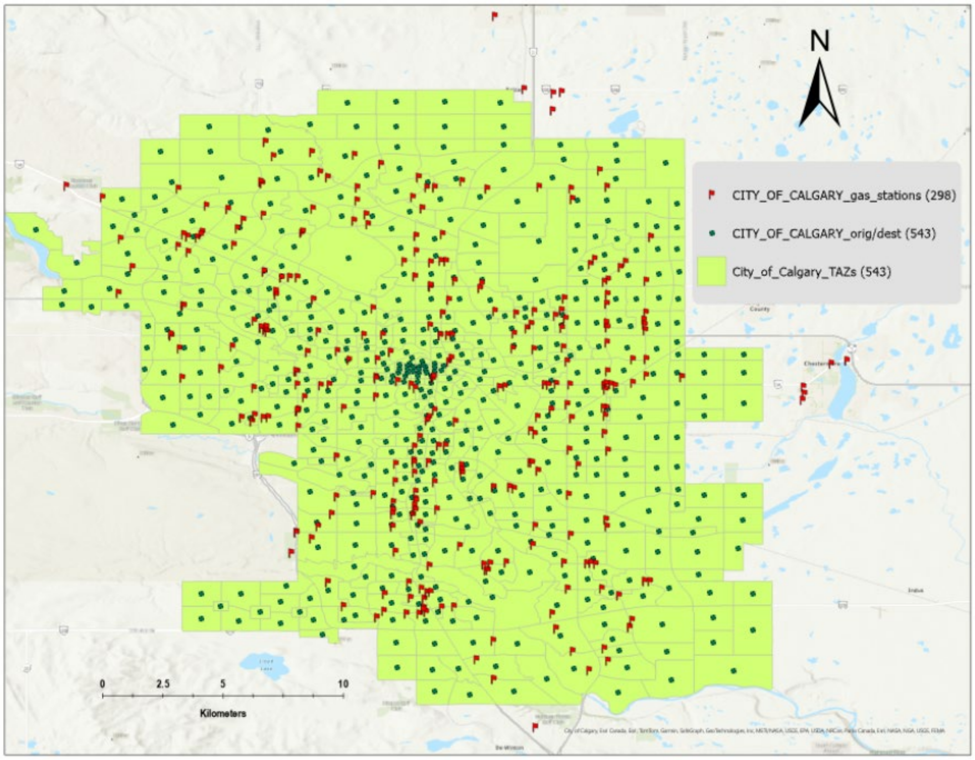

Figure 2 Existing Gasoline Station Distribution in Calgary

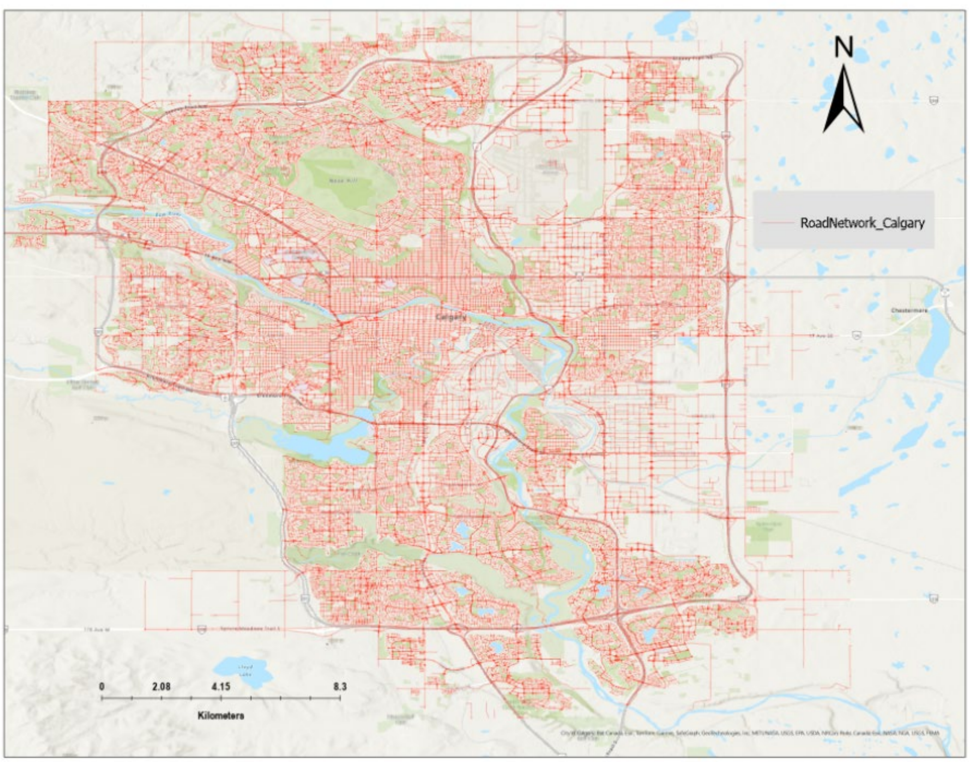

Figure 3 Road Network in Calgary

2.2 EV ADOPTION AND URBAN IMPACTS

2.2.1 Environmental and Urbanization Drivers of EV Adoption

The shift from internal combustion engines (ICEs) to electric vehicles (EVs) is becoming increasingly significant as nations strive to address environmental challenges. The environmental benefits of EVs, particularly as a means of reducing carbon emissions, form the cornerstone of their appeal and their burgeoning adoption across the globe [6]. However, the accessibility and distribution of charging infrastructure remain vital to ensuring EVs become a primary mode of transport for many [7].

2.2.2 Behavioral and Policy Factors Governing EV Uptake

Consumer behavior towards EV adoption depends on a multitude of factors, encompassing economic, environmental, and personal incentives [8]. These behaviors can also be dramatically shaped by policy directives, either propelling or hindering the shift towards EVs [9]. Ongoing urban developments and their interplay with transport emissions further punctuate the complex trajectory of this transition [10].

2.2.3 Charging Infrastructure Needs and Sector Coordination

Meeting charging demand requires coordinated intervention across multiple sectors. Addressing the charging infrastructure gap is a critical part of this transition, requiring collaborative and strategic actions [11]. At the same time, the decline of traditional gasoline stations, driven by reduced fuel demand, has received comparatively less attention. This trend introduces a parallel refueling gap that could affect remaining ICE users and influence accessibility during the long dual-fuel transition period.

2.2.4 Structural Impacts on the Gasoline Retail Industry

The widespread adoption of electric vehicles is expected to profoundly influence the traditional gasoline station industry. While direct studies on the correlation between EV adoption and gas station closures remain limited, several analyses provide insight into this dynamic. Research by the Boston Consulting Group suggests that without substantial business model changes, at least 25 percent of current service stations globally may close by 2035 [12]. Shell's Energy Transition

Strategy similarly highlights plans to close 1,000 gasoline stations globally by 2025, accompanied by significant investment in EV charging infrastructure, reflecting a strategic shift toward low-carbon mobility services [13].

2.2.5 Economic Analyses and Retrofitting Strategies

Economic analyses further contextualize these transitions. Studies such as The Economics of Electric Vehicles by the National Bureau of Economic Research emphasize the substantial reduction in gasoline demand associated with EV adoption and the corresponding downstream impacts on related industries [14]. Research published in Clean Technologies and Environmental Policy explores pathways for retrofitting traditional fuel stations with EV charging infrastructure, suggesting adaptive strategies that may help maintain network resilience during the energy transition [15].

2.2.6 System-Level Transportation Interactions and Grid Integration

Broader studies on EV impacts also show how electrification interacts with transportation operations. A 2023 study by Rodrigues et al. investigated how operating speed influences energy efficiency and traffic-noise outcomes for EV and ICE fleets. The authors found that system-level benefits under high EV penetration are maximized when networks maintain moderate average speeds near 50 km/h, showing that electrification interacts with, but does not automatically resolve, operational transportation challenges [16]. While this does not relate directly to refueling access, it situates EV adoption within a larger systemic context in which multiple infrastructures, including fueling, charging, and roadway operations, evolve simultaneously.

Grid-integration literature expands this perspective. A comprehensive review highlights the technical, regulatory, and infrastructural challenges associated with integrating EVs into electrical distribution networks, identifying emerging constraints and long-term planning needs [17].

2.2.7 Summary of Transition Implications

Although direct studies linking EV adoption to gas station closures are sparse, the existing research collectively indicates that the gasoline station industry is undergoing significant structural change. Trends point toward closures, operational adaptations, or full repurposing as EV adoption accelerates. These findings reinforce the need for targeted research on how fuel-network contraction affects refueling access for ICE users, an underexplored but critical dimension of the dual-fuel transition that this thesis aims to quantify.

2.3 Driver Detour Tolerance

2.3.1 Typical Travel Distances for Essential Urban Services

Studies and surveys indicate that car drivers typically tolerate only a few kilometers of extra travel for routine services. For example, empirical evidence from major Canadian urban contexts suggests that grocery shopping trips generally involve relatively short travel distances. In an analysis of eight large Census Metropolitan Areas, including Toronto, Montréal, Vancouver, Calgary, Ottawa, Winnipeg, Halifax, and Saskatoon, Smith et al. (2023) report that the median home-to-grocery-store driving distance ranged from approximately 4 km to 5 km in 2020, indicating that a majority of urban residents travel only modest distances for essential errands [41]. These findings imply that services located within a few kilometers are commonly perceived as locally accessible in Canadian cities.

2.3.2 Implications for Refueling Detour Tolerance

This behavioral pattern provides a useful benchmark for understanding refueling detour tolerance. Although grocery trips and refueling trips are different in purpose and frequency, both fall under routine urban mobility behavior, where drivers generally prefer short, predictable distances. Consequently, increases of only a few kilometers in refueling detour distance may already impose a noticeable burden, especially for time-constrained commuters or users dependent on ICE vehicles during the transition period. This evidence supports the use of modest, kilometer-scale thresholds when evaluating acceptable refueling detours in this study.

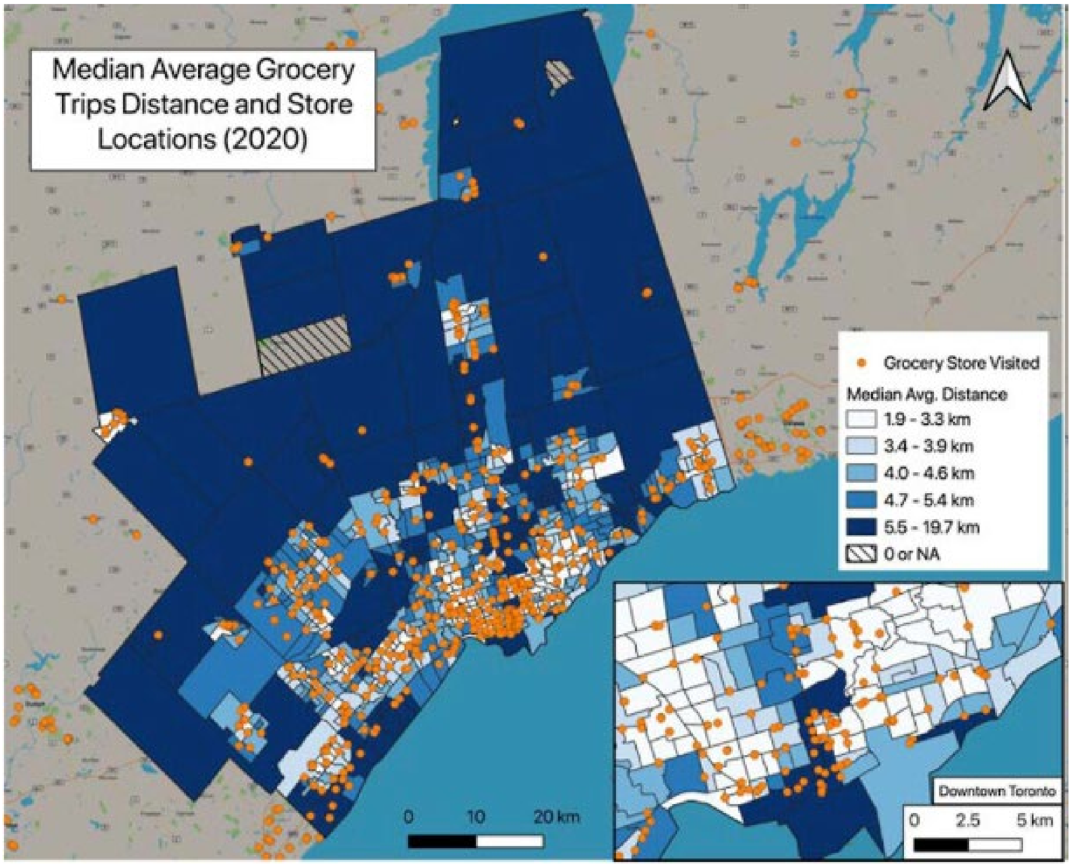

Figure 4 Spatial distribution of median home-to-grocery trip distances in Toronto (2020), illustrating short travel distances for essential services in dense urban areas (adapted from Smith et al., 2023).

Statistics Canada (2020) reports that access to essential services in Canada is typically provided within short travel distances, with approximately 88% of Canadians living within 3 km driving distance of a health care facility, and similarly high proportions of urban residents located within walking distance of daily amenities such as grocery stores, pharmacies, schools, and public transit stops [42]. In a report by the Canadian Board of Education, the walk-zone policy is defined as the maximum distance deemed reasonable for students to walk or cycle to school before qualifying for bus transportation. The defined zone is generally between 1.6 km and 2.4 km, depending on grade configuration [43].

2.3.3 Limits of Driver Willingness to Detour for Fuel

For fuel, the deterrent is even stronger: As gas-station networks contract, understanding drivers' tolerance for refueling detours becomes critical. Chan, Padmanabhan, and Seetharaman (2007) demonstrate through econometric analysis that drivers will rarely travel an extra 1 mile (1.6 km) out of their way to refuel, even when motivated by modest price savings of $0.03 per liter, indicating that refueling detours beyond this distance exceed typical urban driver tolerance [40]. In a recent empirical study, Dorsey, Langer, and McRae (2025) analyze drivers' refueling behavior using high-frequency GPS/vehicle telemetry from the Integrated Vehicle-Based Safety Systems (IVBSS) field operational test in southeast Michigan. They quantify the "excess distance" added when drivers detour to a gas station during an otherwise planned trip, showing that refueling is typically embedded within ongoing travel rather than a stand-alone journey. For trips in their sample (restricted to Michigan and Ohio), the 75th-percentile refueling stop adds only 1.06 miles (~1.7 km) of extra driving, suggesting that most drivers accept only small refueling detours under normal conditions [44].

2.3.4 Implications for Accessibility Evaluation

Taken together, these findings point to a shared expectation that essential urban services should be accessible within short travel distances. Planning practices and observed travel behavior both indicate that distances beyond a few kilometers are generally perceived as burdensome for everyday needs and often require alternative transport or policy intervention. Refueling behavior follows the same logic, with drivers typically incorporating fuel stops into existing trips and showing limited tolerance for additional detours. As fuel stations become less dense during the transition toward electric mobility, increases in refueling distance may therefore translate into meaningful reductions in accessibility for remaining internal combustion engine users.

2.3.5 Conceptual Model of Detour Escalation

To translate these behavioral insights into a fuel-network context, Figure 5 presents a conceptual trajectory of refueling detour under progressive station closures. The curve illustrates how modest early increases can transition into steep, nonlinear escalation once network redundancy collapses.

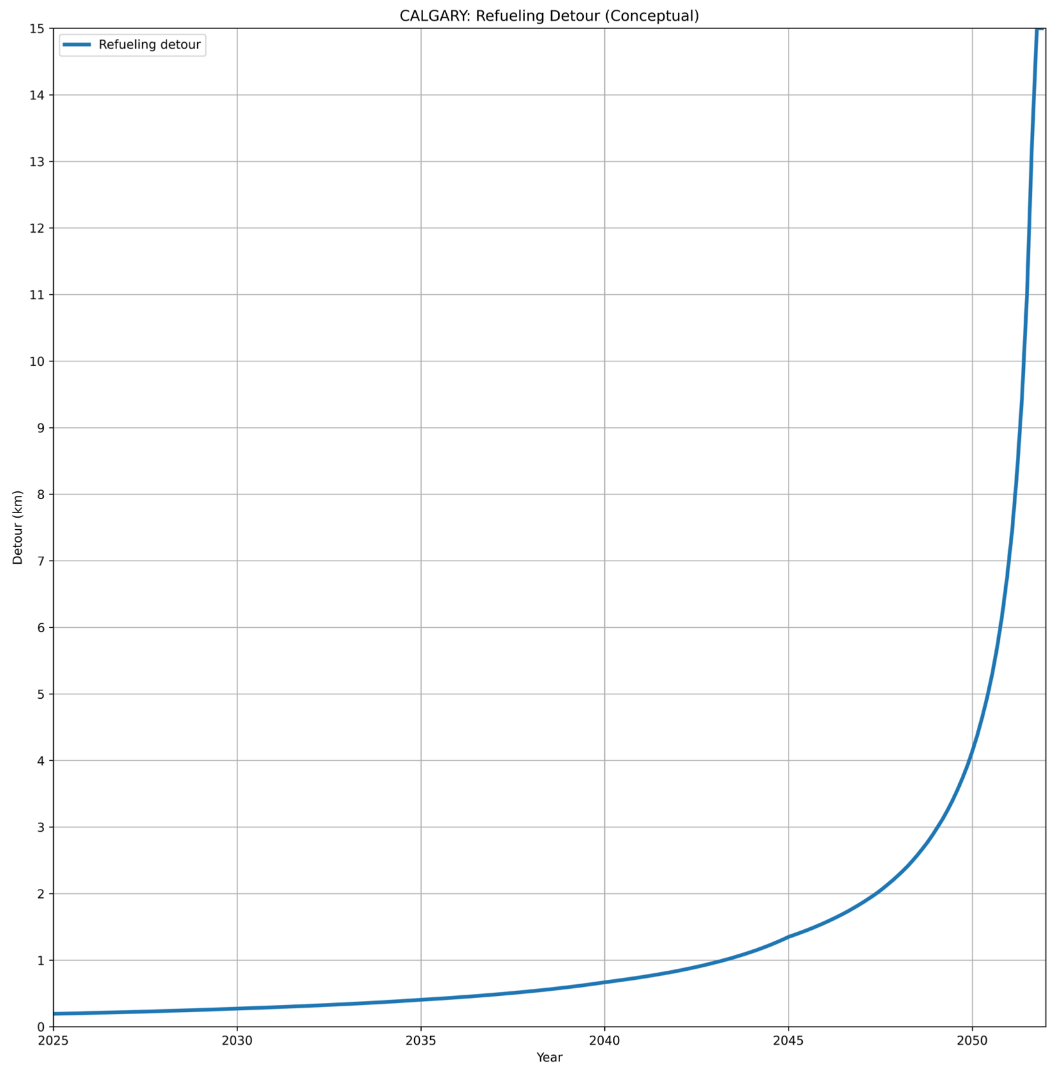

Figure 5 Conceptual trajectory of refueling detour in Calgary as gasoline stations progressively close during mass EV adoption (conceptual).

Early-stage closures remove redundant stations and produce only marginal increases in detour, consistent with literature showing that drivers tolerate only short deviations for routine services. As spatial redundancy erodes, detours could rise more rapidly, reflecting the growing dominance of a few remaining stations. The sharp acceleration after a specific year represents the onset of nonlinear network vulnerability, where the loss of critical stations forces disproportionately long out-of-direction trips.

2.3.6 EV Charging Detour Behavior as an Analogy for ICE Users

Recent studies have also estimated the additional distance or travel time that EV users are willing to accept when detouring to public fast chargers. Although these studies focus on EV drivers, their detour-tolerance measurements operationalize a broader behavioral principle: when refueling or charging infrastructure becomes sparse, travelers can adapt, but only up to a limited margin. By analogy, as gasoline stations progressively close, ICE drivers face a similar trade-off between maintaining their intended trip and incurring an out-of-direction detour. The EV charging literature therefore provides a defensible foundation for framing ICE responses to fuel-station scarcity in terms of acceptable detour thresholds, earlier refueling decisions, route replanting, and increased trip-chaining around available stations. These behavioral constraints help justify the detour-based performance metrics used in this study to evaluate when a fuel network begins to functionally degrade.

2.3.7 Empirical Evidence on EV Charging Detours

In a Danish stated-choice study summarized by Potoglou et al. (2023), electric vehicle drivers were willing to accept approximately 5.6 minutes of additional travel time to save 1 Danish krone per kilowatt-hour (DKK/kWh) on charging costs, and about 0.28 minutes of detour for each incremental increase in charging power (kilometers per minute equivalent). These results indicate that both charging price and charging speed strongly influence route choice and charging decisions [45]. More importantly, the same experiment shows that charger availability dominates both price and speed considerations: drivers were willing to accept approximately 7.9 minutes of additional detour for a guaranteed available charger, whereas an occupied charger was valued at only about 0.5 minutes, underscoring availability as the primary determinant of charging choice [45].

A California preferences study for direct current fast charging (DCFC) found that EV owners value reductions in detour and waiting time: respondents were willing to pay roughly \$0.48 per 100 miles of charging to save one minute of detour time, which equates to about \$0.034 per kilowatt-hour (kWh) on a kWh basis under typical charging session assumptions, and about \$0.94 per 100 miles to eliminate the chance of having to wait at a charger, indicating strong preferences for convenient and reliably accessible charging infrastructure [46]. A Japanese field trial examining battery electric vehicle (BEV) charging behavior in Kanagawa Prefecture found that private EV users were willing to detour up to about 1,750 m for fast charging on working days and about 750 m on non-working days, with commercial users showing lower detour tolerance (~500 m) in both contexts, indicating that day-of-week travel patterns influence charging detour behavior [47]. Willingness to detour is strongly influenced by charger attributes, particularly charging speed and availability. International survey evidence summarized by ACIL Allen and McGuire (2023) indicates that a majority of EV users are willing to go out of their way to access faster or more reliable charging infrastructure [48].

2.3.8 Implications for Fuel-Network Planning

A detailed analysis by Dunsky Energy Advisors emphasizes the scale of investment needed, estimating approximately CAD $20 billion over the next three decades to establish a robust nationwide network of EV chargers [20]. Such infrastructure initiatives not only support EV adoption but also highlight opportunities for the strategic adaptation of existing gasoline stations into hybrid facilities. While this thesis does not model hybrid configurations directly, the literature suggests that repurposing fuel stations to host both EV charging and conventional gasoline services could help preserve refueling accessibility for remaining ICE users during the transition. In principle, these hybridized facilities may reduce potential disruptions in ICE refueling patterns and mitigate localized traffic pressures by maintaining conventional fuel availability alongside expanding charging capacity.

As electric vehicle adoption accelerates, gasoline stations may face increasing economic pressure due to declining fuel demand, raising the risk of network contraction and station closures. Such changes could impose greater refueling distances on remaining internal combustion engine users, creating new logistical and accessibility challenges. Accordingly, urban planners and policymakers must pursue balanced, proactive strategies that expand electric vehicle infrastructure while ensuring that conventional fueling remains sufficiently accessible during the transition period.

As gasoline networks thin out, remaining refueling patterns may begin to mirror behavioral adaptations observed during the early development of public EV charging networks. In those formative years, limited charger availability often required EV drivers to accept some of the longest detours found in normal metropolitan travel. By analogy, ICE drivers operating within a contracting gasoline network may increasingly incorporate modest out-of-direction refueling stops into their regular travel patterns, even though historically such detours were negligible due to high station density.

While the traditional ICE refueling experience involved minimal deviation from an intended route, a shrinking network may normalize slightly longer, yet still practical, refueling deviations. These adjustments would remain consistent with the broader accessibility thresholds observed for essential urban services, where travel beyond a few kilometers is commonly perceived as burdensome. This behavioral context provides a conceptual bridge to quantifying acceptable detour thresholds and evaluating how progressive station closures translate into measurable reductions in fuel accessibility for ICE users.

CHAPTER 3: MODEL CONSTRUCTION

3.1 Overview and Modeling Rationale

This research utilizes an EV-to-ICE ratio model to project future infrastructure availability based on anticipated trends in electric vehicle (EV) adoption. The primary purpose of analyzing these trends is to forecast how increased EV adoption and the corresponding rise in charging infrastructure will affect the availability and distribution of traditional gasoline fuel stations. By understanding these dynamics, the model helps predict scenarios of gasoline station scarcity, highlighting potential disruptions and challenges faced by internal combustion engine (ICE) vehicle users due to reduced accessibility of conventional fueling options. Such analysis is essential for urban planners and policymakers seeking to maintain adequate refueling convenience for remaining ICE users during the transitional phase.

Using comprehensive datasets, this study defines EV adoption trajectories consistent with the federal Electric Vehicle Availability Standard, published in December 2023, which set minimum zero-emission vehicle (ZEV) shares for new light-duty vehicle sales of 20% by 2026, 60% by 2030, and 100% by 2035. The adoption paths used in this analysis are therefore treated as policy-aligned planning scenario (with intermediate years interpolated as needed). [18] Understanding this trajectory enables policymakers and urban planners to proactively assess and address potential disruptions faced by ICE vehicle users as gasoline infrastructure becomes increasingly sparse.

Long-term scenario analysis by the International Council on Clean Transportation (ICCT, 2022) indicates a substantial transformation of Canada's light-duty vehicle fleet by mid-century. In the Baseline scenario, battery-electric vehicles account for approximately 46% of the LDV stock by 2050, with plug-in hybrid vehicles raising total electrified vehicles to about 64%, while internal combustion engine vehicles still comprise roughly 36% of the fleet. In contrast, the Alternative scenarios project electrified vehicles to represent 70–98% of the LDV stock by 2050, implying near-complete electrification. [19]

Figure 6 Light-duty vehicle stock composition in Canada under alternative electrification scenarios, 2020–2050 (adapted from Sen et al., 2022).

As the electric vehicle fleet expands, cities must scale up charging infrastructure while ensuring that gasoline stations remain reasonably accessible for ICE drivers. Maintaining tolerable refueling detours is essential to avoid degrading everyday mobility and convenience during the transition period. Without balanced planning, efforts to meet growing EV charging demand risk unintentionally increasing travel burdens and disrupting urban mobility for both EV and ICE users. Therefore, coordination among federal, provincial, and municipal governments, alongside energy providers, automotive manufacturers, and private-sector stakeholders, becomes essential. Such coordination must be supported by a system-level understanding of how refueling accessibility and detour burdens evolve as electrification progresses.

Within Alberta's unique economic and environmental context, the transition toward EV infrastructure carries particular importance. Historically low fuel prices have contributed to slower EV adoption relative to other Canadian provinces, heightening the need for targeted provincial incentives and strategically planned infrastructure investments. Such an approach can support the acceleration of EV uptake while simultaneously accounting for the needs of remaining ICE users, helping preserve equitable access and travel convenience throughout the transition period.

Additionally, Alberta's considerable emissions from its oil and gas sector, projected to remain substantial even under a net-zero scenario, underscore the importance of accelerating transportation de-carbonization. Alberta-specific strategies must therefore emphasize robust incentives, widespread infrastructure deployment, and clear communication efforts to enhance public acceptance of EVs. Concurrently, efforts must ensure that ICE vehicle users are not disproportionately inconvenienced by diminishing fuel station availability.

By recognizing Alberta's position as Canada's largest provincial emitter of greenhouse gases (GHGs) and addressing its specific challenges related to EV adoption and existing ICE vehicle usage, this research provides targeted insights for policy and planning. Through evaluation of projected EV adoption and the resulting implications for ICE refueling accessibility, this study supports a smooth and equitable transition toward sustainable transportation across Alberta's major cities.

Figure 7 illustrates provincial greenhouse gas (GHG) emissions in Canada, highlighting Alberta's disproportionate contribution to the national total. Alberta accounts for approximately 38% of Canada's GHG emissions despite representing only 12% of the population, underscoring the importance of transportation de-carbonization in the province.

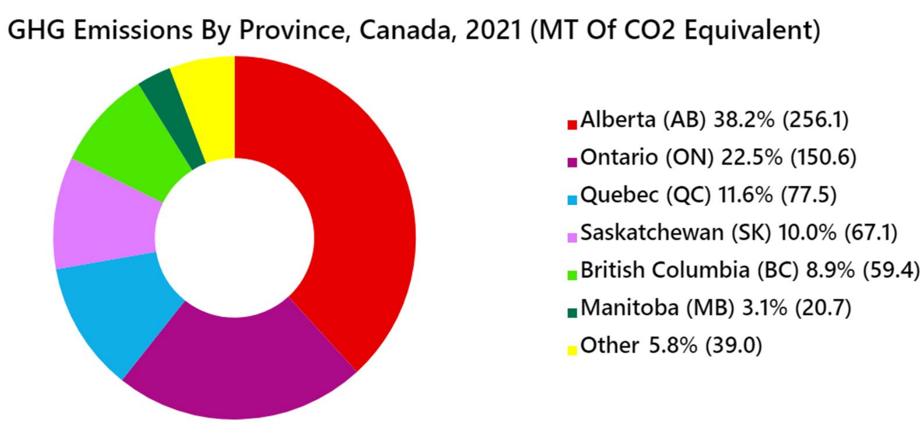

Figure 7 Provincial Greenhouse Gas (GHG) Emissions in Canada, 2021 (Mt CO_2e)

3.2 Methodology Framework

3.2.1 Workflow Components

This study applies a quantitative, geospatial modeling framework to evaluate how increasing electric-vehicle adoption affects gasoline refueling accessibility for internal-combustion-engine (ICE) users in Calgary. The methodology integrates (1) EV-to-ICE ratio projections, (2) proportional gasoline-station closure modeling, (3) Monte Carlo simulation of random closure sequences, and (4) network-based Origin–Destination (OD) cost analysis.

Future EV shares are converted into gasoline-demand reduction trajectories, which are subsequently mapped to milestone-year station-closure fractions. For each milestone, thousands of Monte Carlo iterations simulate different random sequences of station removal. In each iteration, the road network is evaluated twice: (i) the direct Origin–Destination (O→D) distance and (ii) the refueling-constrained Origin–Station–Destination (O→S→D) distance.

3.2.2 Refueling Detour Logic

The difference between these distances yields the per-trip detour distance, while the Average Refueling Detour Distance (ΔD) represents the averaged detour across all OD pairs. Together, these metrics characterize how refueling burdens evolve as gasoline stations become progressively sparse.

3.3 Data and Study Area

3.3.1 Data Acquisition and Integration

The analysis utilizes a comprehensive set of transportation and spatial datasets, including:

- **Traffic flow and origin–destination (OD) trip data**, representing typical vehicular movement patterns across Calgary.
- **EV and ICE vehicle adoption datasets** describing temporal changes in fleet composition under baseline and alternative transition scenarios.
- **Road network data**, including roadway geometry, connectivity, and link-level travel-cost attributes used for network-based accessibility analysis.

- **Transportation Analysis Zones (TAZs) and postal code boundary datasets**, used as the primary spatial units for aggregating demand, assigning refueling infrastructure, and enabling consistent comparisons.
- **Urban and municipal boundary layers** distinguishing urban, suburban, and regional contexts.
- **Gasoline station location and availability data** consisting of geocoded records for over 1,500 stations distributed across roughly 3,000 spatial units (TAZs and postal-code zones combined), with simulated station closures applied to reflect declining gasoline demand.

3.3.2 Conceptual Network Framework (O→D vs O→S→D)

Conceptually, the analytical framework compares travel routes between origins and destinations (O→D) with refueling-constrained travel paths that require an intermediate stop at a gasoline station (O→S→D) on the same road network. This structure enables explicit quantification of additional travel distance attributable to refueling and provides a consistent basis for assessing how refueling detour evolves as gasoline stations are progressively removed during EV adoption. The approach establishes a coherent network logic for evaluating accessibility impacts while maintaining comparability across closure scenarios and spatial contexts.

3.3.3 OD Representation for Calgary Case Study

For the Calgary case study, origin–destination (OD) pairs were represented using Transportation Analysis Zone (TAZ) centroids provided by the provincial travel-demand datasets. OD pairs were filtered to retain only trips whose origin and destination TAZs fall within the Calgary municipal boundary. This zoning approach preserves intra-urban spatial resolution while maintaining consistency with observed travel-demand data used in the O–D network analysis.

3.4 Modeling Gasoline Station Closures

Building upon the policy-anchored electric-vehicle (EV) adoption trajectories, this study models the resulting decline in internal-combustion-engine (ICE) vehicle prevalence and the corresponding reduction in gasoline demand. As EV adoption increases in accordance with Canada's Zero-Emission Vehicle (ZEV) mandate, the gasoline demand attributable to the ICE fleet contracts over time, reflecting the shrinking share of ICE vehicles within the overall light-duty vehicle stock.

Declining gasoline demand reduces the economic viability of retail fuel stations, particularly in urban areas where EV uptake tends to accelerate earliest. Under sustained demand contraction, a portion of stations is expected to exit the market, leading to a gradual reduction in the overall fuel-station network. To represent this transition, the model assumes that the fraction of stations that close in a given year is proportional to the fraction of gasoline demand lost relative to the 2025 baseline. This proportional-closure assumption provides a tractable mechanism for linking fleet-level electrification trajectories to infrastructure attrition, while allowing closure magnitudes to vary across EV adoption scenarios.

Although gasoline stations in reality close selectively based on local market conditions, this study applies randomized station removal within a Monte Carlo simulation framework to capture uncertainty in closure order and spatial pattern. Randomization enables the evaluation of network vulnerability under a wide spectrum of plausible closure sequences rather than a single deterministic path.

These modeled closure patterns form the input to subsequent network-based accessibility analysis, enabling assessment of how progressive infrastructure loss affects refueling detours, network resilience, and the emergence of potential fuel-desert conditions during the transition from ICE-dominant to electrified mobility.

3.5 Network Analysis Using ArcGIS Pro

To quantify the impact of gasoline-station closures on internal combustion engine (ICE) vehicle users, the study performs a network-based accessibility analysis using ArcGIS Pro's Network Analyst environment. The road network is modeled with travel distance as the impedance, enabling shortest-path calculations under both direct (O→D) and refueling-constrained (O→S→D) conditions.

The analysis consists of three main components:

3.5.1 Origin–Destination (OD) Cost Matrix Computation

ArcGIS Pro is used to generate all network distances required for the simulation. Baseline O→D distances are computed once, along with Origin–Station (O→S) and Station–Destination (S→D) distances for every candidate gasoline station. Refueling-constrained distances are not computed in ArcGIS; instead, they are constructed analytically by summing the precomputed O→S and S→D distances and selecting the shortest feasible O→S→D combination for each OD pair during the simulation.

3.5.2 Gasoline Station Closure Scenarios

Gasoline station closure scenarios reflect the progressive decline in fueling availability associated with long-term EV adoption. To avoid computationally expensive network recalculations at each closure level, all ArcGIS Network Analyst computations are performed **once**. For every OD pair, a ranked list of candidate stations is created based on total refueling path cost d(O→S)+d(S→D). These precomputed candidate lists are then used in the Monte Carlo simulation, where stations are removed randomly according to predefined closure fractions. At each iteration, the best refueling option is the highest-ranked station that remains open.

3.5.3 Refueling Distance Impact Assessment

During the Monte Carlo simulation, refueling-constrained distances are dynamically updated using the fixed O→D, O→S, and S→D tables generated in ArcGIS Pro. For each closure level, the shortest feasible O→S→D path is determined by scanning the remaining open stations in the OD's ranked candidate list. This approach ensures consistent, repeatable evaluation of refueling accessibility while eliminating the need for expensive network re-computation during scenario analysis.

3.5.4 Directionality and the Need for Separate O–D, O→S, and S→D Analyses

In a directed urban road network, the shortest path between two points depends on travel direction. One-way segments, turn restrictions, medians, and intersection controls all create asymmetry, meaning that the path from A to B is often not the same as the path from B to A. For refueling analysis, this directional structure has two important consequences.

First, the direct O–D route used as the baseline for detour calculation must reflect the directed shortest path under actual network rules. Second, a refueling trip cannot be modeled as a single undirected deviation. Instead, it consists of two distinct directed components: the access leg from the origin to a station (O→S) and the continuation leg from the station to the destination (S→D). These two paths can differ substantially even for the same trip. For example, a driver leaving home, refueling, and returning to the same point may follow completely different outbound and inbound routes because of one-way streets or turn prohibitions.

For this reason, the study computes O–D, O→S, and S→D cost matrices separately in ArcGIS Pro. The refueling-constrained path is then analytically constructed as O→S→D = O→S + S→D, selecting the station that minimizes this sum across all available gas stations for a specific origin and destination pair. A localized ArcGIS illustration (Figure 8) demonstrates this asymmetry: red lines show O→S access paths, while blue lines show S→D return or continuation paths. This decomposition ensures that detour estimates reflect the true structure of the directed network, rather than simplified or symmetric approximations.

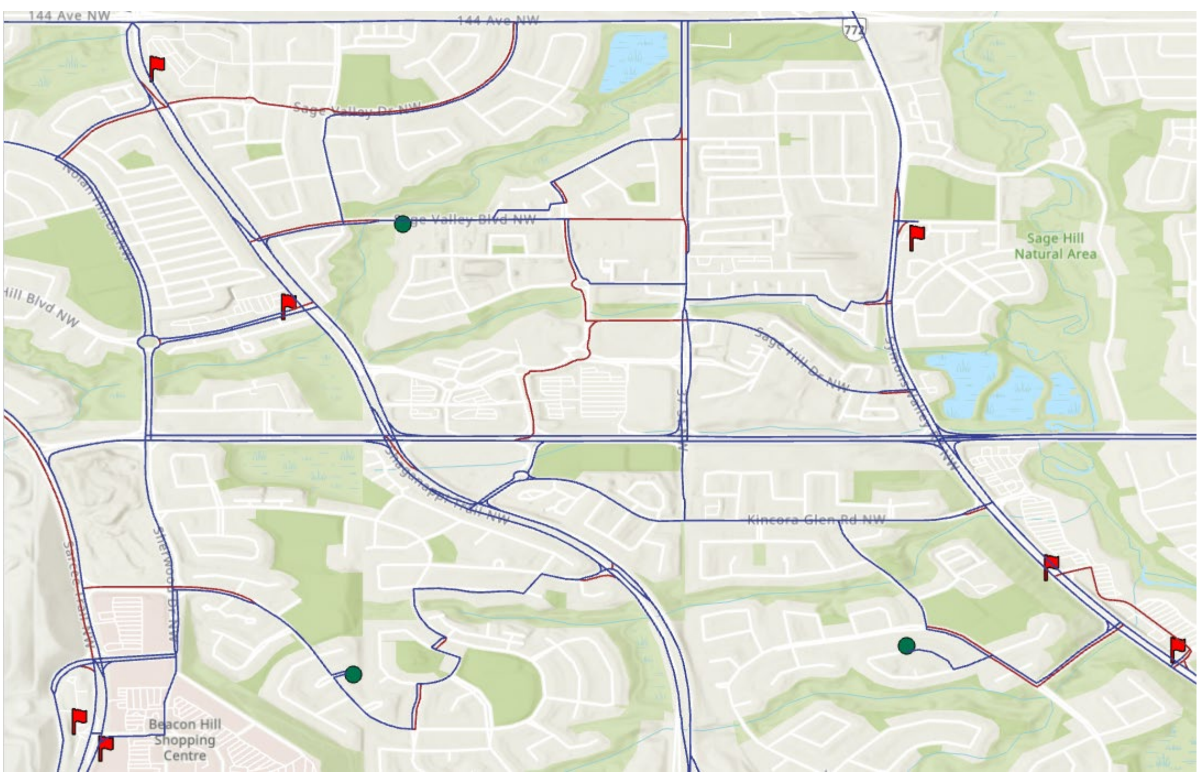

Figure 8 Directional Shortest-Paths for O→S and S→D Routes

*Note: **Red lines** indicate O→S access routes; **blue lines** show S→D continuation routes. **Green points** denote origin/destination points, and **red flags** indicate available gasoline-station locations. Directional network constraints (one-way links, turn prohibitions) create asymmetric shortest paths.*

3.6 Cost Matrix Development

The refueling analysis is built upon a single set of network distance tables generated once in ArcGIS Pro using the OD Cost Matrix tool. Three distance components are computed: (i) direct Origin–Destination (O→D) distances, (ii) Origin–Station (O→S) distances for every candidate gasoline station, and (iii) Station–Destination (S→D) distances for the same stations. These tables constitute the complete cost matrix required for all refueling analyses.

Each OD pair is additionally assigned a precomputed, distance-ranked list of candidate stations, sorted by total refueling-path cost d(O→S) + d(S→D). This ranked list allows refueling distances to be reconstructed analytically without any need for repeated network calculations.

During the Monte Carlo simulation, fuel stations are removed stochastically according to the predefined closure fractions. For each closure level and each OD pair, the shortest feasible refueling path is obtained by scanning the OD's ranked candidate list and selecting the highest-ranked station that remains open. Because all O→D, O→S, and S→D distances are fixed and computed only once, accessibility impacts at each closure level emerge directly from the evolving set of available stations rather than from new network computations.

3.7 Implications for Urban Planning and Policy

Although full policy analysis is presented in later chapters, the methodological framework developed in this study is designed to generate metrics directly relevant to urban planning and transportation policy. By quantifying how gasoline station closures affect refueling accessibility across different urban areas, the model enables the identification of zones that may become increasingly vulnerable during the transition from ICE to EV mobility. These outputs can inform subsequent evaluations of policy responses, such as retaining strategically important stations, deploying hybrid refueling facilities, or expanding EV charging infrastructure, to mitigate potential accessibility challenges for remaining ICE users.

3.8 EV vs. ICE Vehicle Trends in Canada (2010–2050)

Canada's light-duty vehicle (LDV) landscape is undergoing a rapid transition from internal combustion engine (ICE) cars to electric vehicles (EVs). LDVs are responsible for approximately 50% of Canada's transportation sector GHG emissions. Transport Canada defines LDVs as cars, sports utility vehicles, or light trucks with a Gross Vehicle Weight Rating of 4,535 kg or below [21]. This section examines historical data (2010–2024) and forecasted trends (to 2050) in EV and ICE stocks, focusing on light-duty vehicles. Year-by-year or interval-based data on vehicle stocks and shares are presented, highlighting inflection points, outlining policy-driven shifts and forecasting assumptions. Data points are drawn from reputable sources such as Transport Canada, Natural Resources Canada (NRCan), the International Energy Agency (IEA).

3.8.1 Historical EV and ICE Stock in Canada (2010–2023)

Table 1 Total Light-Duty Vehicles in Canada (2010–2023) Retrieved from Statistics Canada. Table 23-10-0308-01 Vehicle registrations, by type of vehicle and fuel type [23], [24]

Year	Total Road Motor Vehicle Stock	Light-Duty Vehicle (LDV) Stock	LDV Share of Total Road Motor Vehicles	ZEV Stock (BEV+PHEV)	ZEV Share of Total LDV	New ZEV Sales (% of New Sales)	ICE Stock	ICE Share of Total LDV	New ICE Sales (% of New Sales)
2010	21,847,601	20,267,982	92.8%	0	0	0	~20,267,982	100.0 %	100.0 %
2011	22,246,916	20,608,101	92.63 %	518	~0.003%	~0.03%	~20,607,500	~100.0%	~99.97 %
2012	22,366,270	20,651,993	92.35%	1989	~0.01%	~0.1%	~20,650,000	~99.99%	~99.90 %
2013	23,006,222	21,261,660	92.45%	3150	~0.01%	~0.1%	~21,258,000	~99.98%	~99.90 %
2014	23,538,817	21,729,596	92.32%	5,372	~0.02%	~0.2%	~21,724,000	~99.97%	~99.80 %
2015	23,923,806	22,067,778	92.27%	6,888	~0.03%	~0.3%	~22,060,000	~99.96%	~99.70 %
2016	24,269,868	22,410,030	92.31%	12009	~0.05%	~0.4%	~22,395,000	~99.94%	~99.60 %
2017	24,612,692	22,725,565	92.50%	43,476	~0.2 %	~1.2%	22,681,649	~99.8 %	~98.80 %
2018	25,036,977	23,099848	92.19%	76,016	~0.33 %	~2.0%	23,023,313	~99.67%	~98.00 %
2019	25,418,224	23,445,284	92.24%	126,106	~0.55 %	~3.1%	23,318,509	~99.45%	~96.90 %
2020	25,749,657	23,757,138	92.27%	180,187	~0.75 %	~3.8%	23,576,215	~99.25%	~96.20 %
2021	26,248,616	24,123,190	91.91%	248,653	~1.0 %	~5.6%	23,873,753	~99.0%	~94.40 %
2022	25,757,030	23,620,574	91.76%	341,141	~1.5 %	~8.9%	23,278,610	~98.5%	~91.10 %
2023	25,688,408	23,551,759	91.65%	472,742	~2.1 %	~11.8%	23,078,207	~97.9%	~88.20 %

Notes: *ZEV stock includes* ***battery electric vehicles (BEVs)*** *and* ***plug-in hybrid vehicles (PHEVs)****. New EV sales share is the percentage of* ***new light-duty vehicle registrations*** *that are EVs.*

The above table summarizes Canada's light-duty vehicle registration data compiled from Statistics Canada [23], [24]. The data indicate that electric vehicle (EV) adoption in Canada remained negligible prior to 2011, followed by a sustained acceleration beginning after 2015, coinciding with technological improvements, expanded model availability, and the introduction of supportive federal and provincial policies. EVs accounted for approximately 0.3% of new light-duty vehicle sales in 2015, increasing to 3.1% in 2019 and 3.8% in 2020. Adoption continued to accelerate thereafter, reaching 5.6% in 2021, 8.9% in 2022, and 11.8% in 2023. By July 2024, zero-emission vehicles (ZEVs) represented 13.8% of all new light-duty vehicle sales, up from 11.8% in July 2023 [18].

Figure 9 illustrates trends in total road motor-vehicle registrations and light-duty vehicle (LDV) stocks in Canada from 2010 to 2023. Both series exhibit steady growth throughout the pre-pandemic period, reflecting population increases, economic expansion, and rising household vehicle ownership. Vehicle stocks peak around 2021 before experiencing a modest decline, driven largely by COVID-19–related supply-chain disruptions, including semiconductor shortages, raw-material constraints, and shipping delays, that slowed new-vehicle production and deferred deliveries. These constraints temporarily shifted demand toward the used-vehicle market, moderating the growth of registered vehicles during 2021–2023.

This trend provides important context for the EV transition analysis, as fluctuations in total LDV stock influence both ICE demand trajectories and the timing of infrastructure pressures examined in subsequent sections.

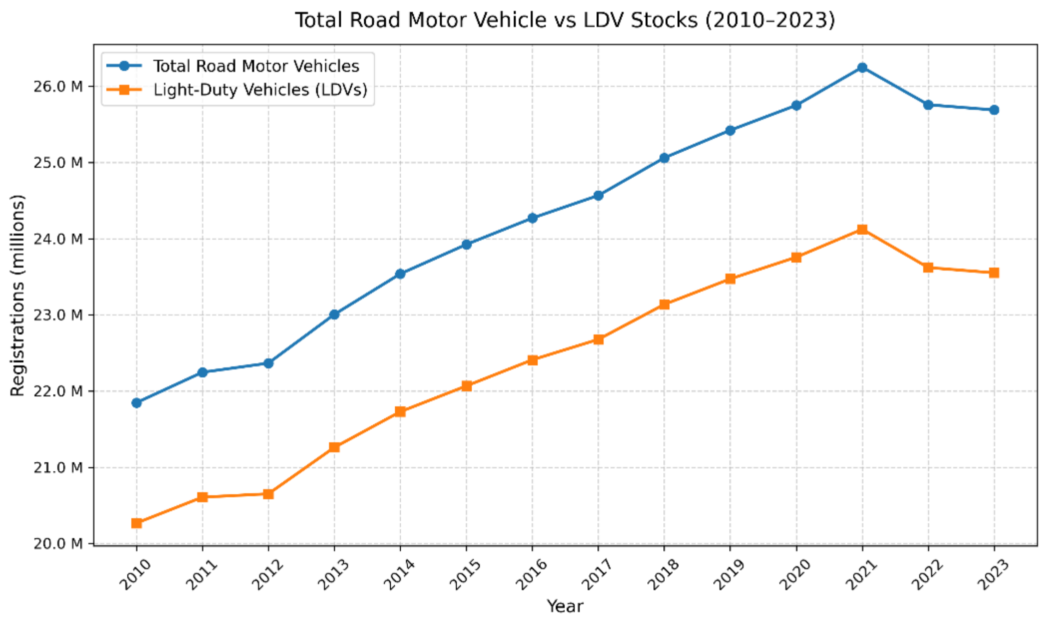

Figure 9 Trends in Total Motor-Vehicle and LDV Registrations in Canada (2010–2023)

Light-duty vehicle (LDV) registration data presented in Table 1 indicate a divergence between overall new vehicle registrations and zero-emission vehicle (ZEV) adoption trends in Canada. While total new vehicle registrations exhibit a gradual decline after 2017, reflecting market saturation, economic uncertainty, and an increased reliance on the used-vehicle market, ZEV sales continued to accelerate over the same period. This decoupling suggests that EV growth has occurred despite broader headwinds in the automotive market.

Analysis of ICE and ZEV registrations derived from Table 1 further highlights a structural shift in Canada's vehicle fleet composition. ZEV adoption has increased steadily, driven by expanded model availability, sustained federal and provincial incentive programs, and rising environmental awareness, while ICE vehicle registrations have correspondingly declined. Together, these trends signal a transition away from ICE dominance toward a progressively electrified LDV fleet, providing the empirical basis for subsequent modeling of gasoline demand reduction and refueling infrastructure contraction.

3.8.2 ICE Stock & New-Sales Share

Figure 10 shows trends in the internal combustion engine (ICE) light-duty vehicle fleet and its share of new-vehicle sales in Canada from 2010 to 2023. The total ICE stock increased from approximately 20.3 million vehicles in 2010 to a peak of about 24.1 million in 2021, reflecting slow fleet turnover and the long operational lifespan of legacy ICE vehicles.

In contrast, ICE vehicles continued to dominate new-vehicle sales through the mid-2010s but began a steady decline thereafter, falling to roughly 88% by 2023. This reduction corresponds with the growing market penetration of zero-emission vehicles (ZEVs), signaling an early shift in purchase behavior even while the existing ICE fleet remains large.

Together, these trends highlight a key feature of Canada's vehicle transition: new-sales electrification progresses earlier than fleet turnover, implying that gasoline demand and therefore gasoline-station viability declines more slowly than the rise in EV adoption might suggest.

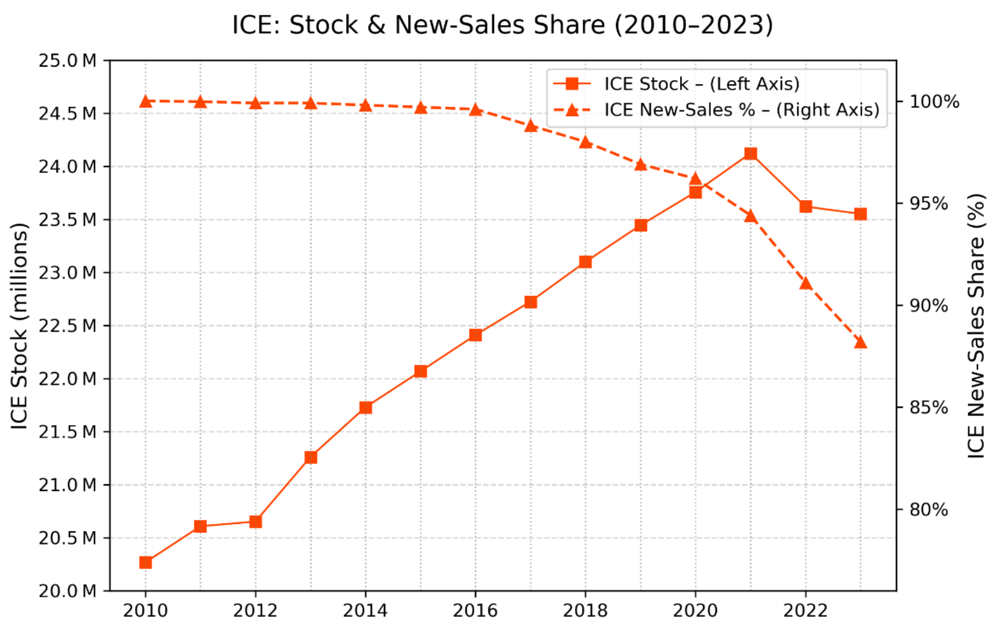

Figure 10 ICE Light-Duty Vehicle Stock and New-Sales Share in Canada (2010–2023)

3.8.3 ZEV: Stock & New-Sales Share

Figure 11 presents the evolution of zero-emission vehicle stocks and their share of new light-duty vehicle sales in Canada from 2010 to 2023. ZEVs, including battery electric and plug-in hybrid vehicles were virtually absent from the national fleet prior to 2012. Subsequent expansion in model availability, coupled with federal and provincial purchase incentives, accelerated adoption, resulting in a rapid increase in stock to approximately 0.47 million vehicles by 2023.

ZEVs accounted for less than 0.5% of new LDV sales through 2016, after which their market penetration rose sharply, reaching about 11.8% by 2023. This inflection point aligns with the introduction of strengthened federal ZEV mandates and expanded provincial incentive programs, marking a structural shift in the composition of new-vehicle purchases.

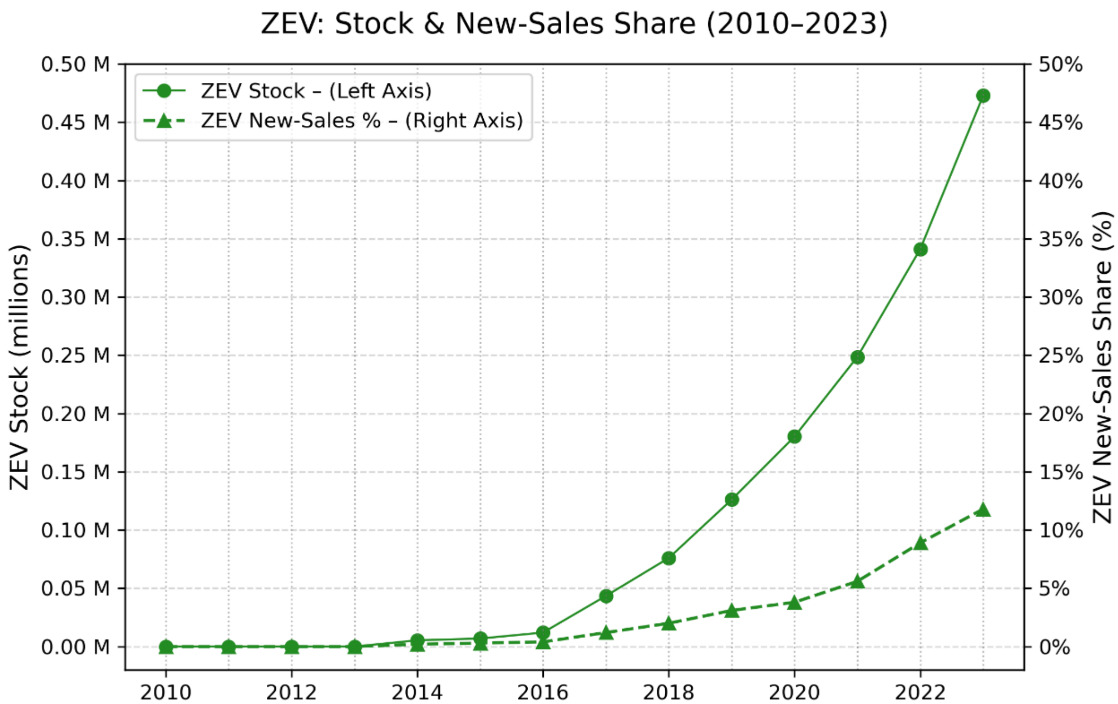

Figure 11 ZEV Light-Duty Vehicle Stock and New-Sales Share in Canada (2010–2023)

Together, these trends reveal a transitional period in Canada's light-duty vehicle market: the legacy ICE fleet remains large and slow to turnover, while new-vehicle registrations are increasingly shifting toward ZEV technologies. This coexistence of a substantial ICE stock with a rapidly decarbonizing new-sales market underscores the need for modeling approaches that capture both the slow decline of gasoline demand and the accelerating pace of electrification.

In the Canadian context, Alberta presents a distinctive adoption pathway shaped by historically lower EV uptake relative to provinces such as Quebec, British Columbia, and Ontario. This pattern is associated with the absence of provincial purchase incentives, comparatively low fuel prices, and consumer preferences for larger vehicles such as trucks and SUVs. Nonetheless, recent adoption figures point to accelerating interest. As of March 2024, Alberta reported approximately 14,200 registered EVs, an increase of nearly 150% over two years, although this still represents a modest share of the provincial fleet. Infrastructure growth has been more rapid: by March 2025, Alberta surpassed 1,800 public charging ports, up from 255 in 2022, making it the fourth province to reach this threshold [25].

Despite these developments, Alberta does not offer provincial EV purchase rebates and has implemented a $200 annual EV registration fee to offset declining fuel-tax revenues. At the federal level, the iZEV program previously offering rebates up to $5,000 was paused in early 2025 following the depletion of allocated funds [26]. Consequently, EV growth in Alberta has been driven primarily by federal policy and consumer preference rather than provincial incentives. Given Alberta's extensive heavy-industry base and reliance on long-distance freight movement, the electrification of commercial and medium/heavy-duty fleets remains an emerging, rather than immediate, focus area.

These provincial characteristics emphasize the importance of evaluating EV adoption and gasoline-station viability within a regional context, as Alberta's slower but accelerating transition influences both the timing and magnitude of gasoline demand decline incorporated into the modeling framework.

3.9 Analysis of ICE Vehicle Decline in Canada (2024–2050)

Canada's commitment to achieving net-zero greenhouse gas emissions by 2050 includes binding targets for Zero-Emission Vehicle (ZEV) adoption in the Light-Duty Vehicle (LDV) sector. The federal government has established minimum ZEV sales targets of 20% by 2026, 60% by 2030, and 100% by 2035 for new LDVs under the Electric Vehicle Availability Standard finalized in December 2023 [27]. These policy targets imply a progressive reduction in the Internal Combustion Engine (ICE) vehicle fleet over time, with direct implications for gasoline demand and the long-term viability of gasoline refueling infrastructure.

To support subsequent modeling of gasoline station closures, this analysis estimates the decline in ICE vehicle stock from 2026 to 2050 by combining projections of total LDV stock with ZEV stock-share trajectories derived from government targets and academic literature. Total LDV stock is treated as a boundary condition, while ICE stock evolution is derived as ZEV adoption increases. These projections provide the quantitative basis for forecasting gasoline demand contraction and evaluating refueling infrastructure resilience during the transition period.

3.9.1 Total LDV Stock Projections

Total LDV stock is projected using a linear regression model fitted to historical registration data from 2010 to 2023, yielding an R^2 value of 0.932. The resulting trendline is extrapolated through 2050 to establish long-term LDV stock milestones (Figure 12).

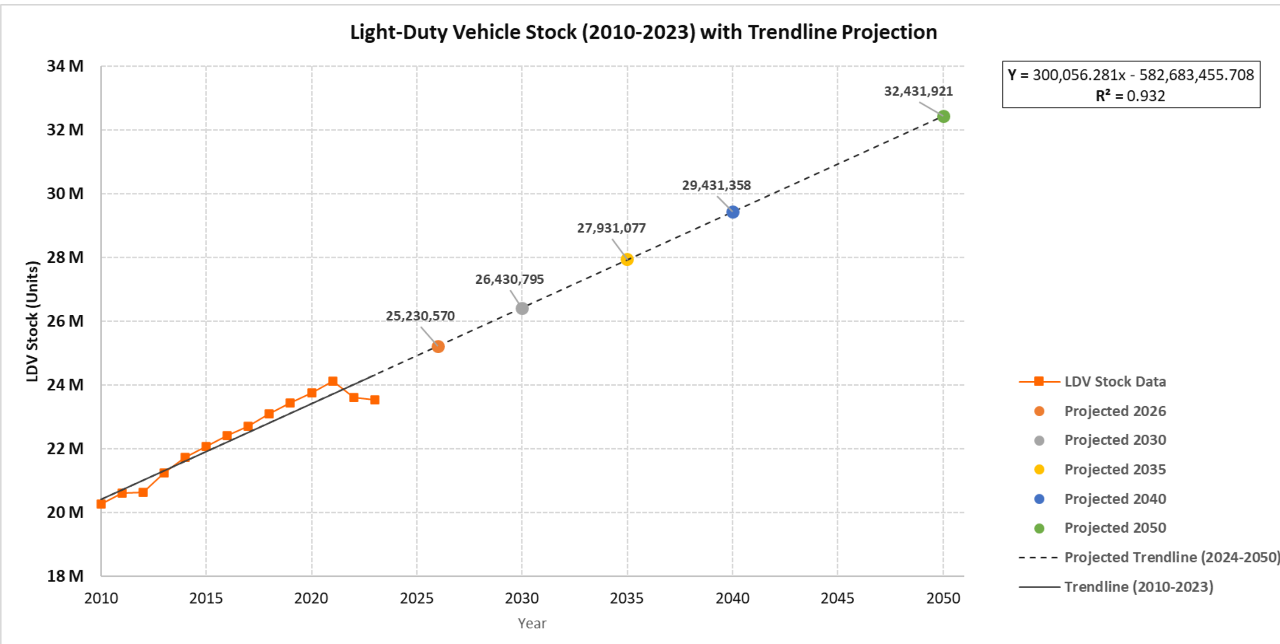

Figure 12 Light-Duty Vehicle Stock in Canada (2010–2023) with Trendline Projection to 2050

The fitted trendline indicates continued growth in the Canadian LDV fleet, reaching approximately 25.23 million vehicles by 2026, 26.43 million by 2030, 27.93 million by 2035, 29.43 million by 2040, and 32.43 million by 2050. This projection reflects underlying demographic and economic momentum rather than assumptions regarding powertrain composition. As such, it represents an upper-bound estimate of total vehicle stock and may overstate realized growth due to market saturation, increasing urban density, and shifts toward public transit, active transportation, and shared mobility.

Developing a more precise long-term forecast would require integrated modeling of population growth, travel behavior, land-use change, infrastructure investment, and policy feedback mechanisms, an extensive scope that lies beyond the scope of this study. Nevertheless, the use of milestone-based LDV stock estimates provides a consistent and transparent framework for deriving ICE vehicle decline under alternative ZEV adoption scenario and for evaluating downstream impacts on gasoline demand and refueling infrastructure viability.

3.9.2 ZEV Stock Share Estimation

Beginning with the 2026 model year, federal regulations require that a minimum of 20% of new light-duty vehicles offered for sale be zero-emission vehicles (ZEVs), with this share increasing to 60% by 2030 and reaching 100% by 2035 [27]. These targets define the trajectory of ZEV penetration in new vehicle sales rather than immediate changes in the on-road fleet.

To translate annual ZEV sales targets into ZEV stock shares, the analysis assumes an average light-duty vehicle lifespan of 12-15 years. Thus, ZEV stock accumulation reflects the gradual replacement of retiring internal combustion engine vehicles rather than instantaneous fleet turnover. The resulting ZEV sales trajectory, illustrated in the accompanying table and chart, indicates a rapid acceleration in ZEV inflows between 2026 and 2035, followed by a progressive saturation of the vehicle stock in subsequent years.

This stock-based interpretation of sales mandates provides a realistic temporal framework for estimating ICE vehicle decline and the associated reduction in gasoline demand.

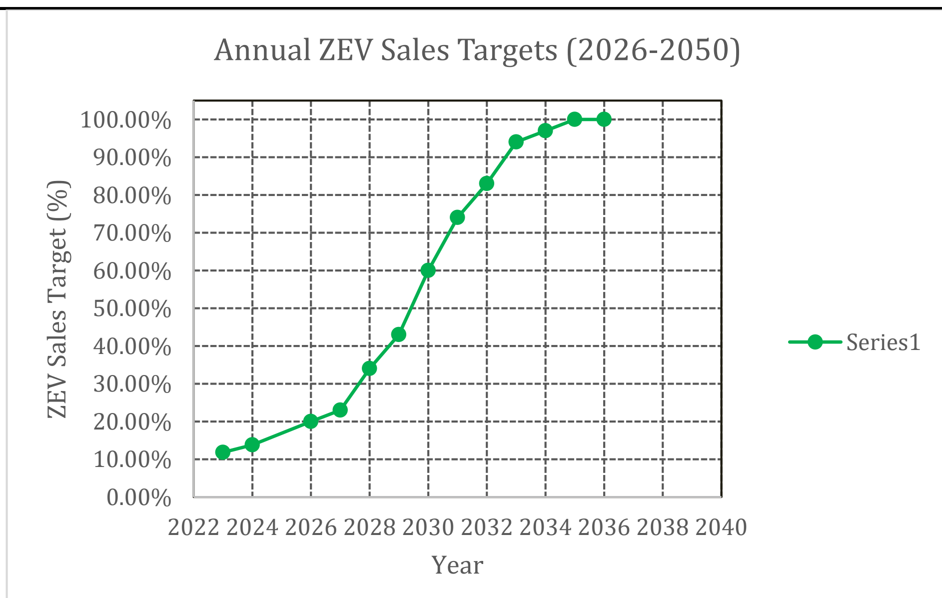

Figure 13 Annual zero-emission vehicle (ZEV) sales targets in Canada, 2026–2050.

In 2023, zero-emission vehicles (ZEVs) accounted for approximately 2.1% of the total light-duty vehicle (LDV) stock, despite representing 11.8% of new vehicle sales. This disparity reflects the slow evolution of vehicle stock relative to sales flows, as light-duty vehicles typically remain in service for approximately 12–15 years. Consequently, even if internal combustion engine (ICE) vehicle sales decline to near zero by 2035, a substantial number of ICE vehicles are expected to remain in operation well into the 2040s under any plausible net-zero transition pathway.

This structural lag between changes in new vehicle sales and on-road fleet composition is expected and unavoidable. Consistent with this dynamic, government projections from the Canada Energy Regulator's "Canada's Energy Future 2023" report under the Global Net-Zero Scenario estimate ZEV stock shares of approximately 14% by 2026, 24% by 2030, 46% by 2035, 66% by 2040, 83% by 2045, and 96% by 2050, indicating a gradual but substantial replacement of ICE vehicles over time [28] (Table 2).

Table 2 Projected LDV, ZEV, and ICE Vehicle Stock in Canada (2026–2050)

Model Year	Total LDV Stock (millions)	ZEV Sales Target (%)	ZEV Stock Share	ZEV Stock (millions)	ICE Sales Estimates (%)	ICE Stock Share	ICE Stock (millions)
2023	23.55	11.80%	2.10%	0.49	88.20%	97.90%	23.06
2024	24.63	14%	5.52%	1.36	86.20%	94.48%	23.27
2025	24.93	17%	9.10%	2.27	83.50%	90.90%	22.66
2026	25.23	20%	14.00%	3.53	80%	86.00%	21.70
2027	25.53	23%	16.26%	4.15	77%	83.74%	21.38
2028	25.83	34%	19.84%	5.12	66%	80.16%	20.71
2029	26.13	43%	23.42%	6.12	57%	76.58%	20.01
2030	26.43	60%	24.00%	6.34	40%	76.00%	20.09
2031	26.73	74%	30.58%	8.17	26%	69.42%	18.56
2032	27.03	83%	34.16%	9.23	17%	65.84%	17.80
2033	27.33	94%	37.74%	10.31	6%	62.26%	17.02
2034	27.63	97%	41.32%	11.42	3%	58.68%	16.21
2035	27.93	100%	45.50%	12.71	0%	54.50%	15.22
2036	28.23	100%	48.48%	13.69	0%	51.52%	14.54
2037	28.53	100%	52.06%	14.85	0%	47.94%	13.68
2038	28.83	100%	55.64%	16.04	0%	44.36%	12.79
2039	29.13	100%	59.22%	17.25	0%	40.78%	11.88
2040	29.43	100%	66.00%	19.42	0%	34.00%	10.01

2041	29.73	100%	66.38%	19.74	0%	33.62%	10.00
2042	30.03	100%	69.96%	21.01	0%	30.04%	9.02
2043	30.33	100%	73.54%	22.31	0%	26.46%	8.03
2044	30.63	100%	77.12%	23.62	0%	22.88%	7.01
2045	30.93	100%	83.00%	25.67	0%	17.00%	5.26
2046	31.23	100%	84.28%	26.32	0%	15.72%	4.91
2047	31.53	100%	87.86%	27.70	0%	12.14%	3.83
2048	31.83	100%	91.44%	29.11	0%	8.56%	2.72
2049	32.13	100%	94.82%	30.47	0%	5.18%	1.66
2050	32.43	100%	96.00%	31.13	0%	4.00%	1.3

Note: *Blue cells indicate observed/historical values from publicly available datasets (base years). Green cells indicate scenario anchor points taken directly from cited sources: (i) federal interim ZEV new light-duty vehicle (LDV) sales requirements (minimum sales shares for 2026, 2030, and 2035), and (ii) the Canada Energy Regulator (CER), Canada's Energy Future 2023, Global Net-Zero scenario for ZEV stock share benchmark years (2026, 2030, 2035, 2040, 2045, 2050). All non-blue, non-green cells are modelled values derived by interpolation between anchor years and extrapolation beyond available anchors (where applicable), with totals and complementary ICE shares/stocks computed by identity.*

These projections assume continued adherence to Canada's ZEV sales mandates and effective automaker compliance through regulatory enforcement mechanisms.

The following chart (Figure 14) presents the projected evolution of Canada's light-duty vehicle (LDV) fleet from 2010 to 2050, combining historical observations (2010–2023; Table 1) with projections (2024–2050; Table 2). Total LDV stock increases steadily over time, while the composition of the fleet shifts from near-total dominance of internal combustion engine (ICE) vehicles toward zero-emission vehicles (ZEVs). ICE vehicle stock declines gradually following the acceleration of ZEV adoption, reaching near parity with ZEV stock around the mid-2030s and continuing to contract thereafter. This transition reflects the combined effects of Canada's ZEV sales mandates and the lagged turnover of the vehicle fleet due to vehicle longevity, underscoring the persistence of a prolonged dual-fuel transition period relevant for refueling infrastructure planning.

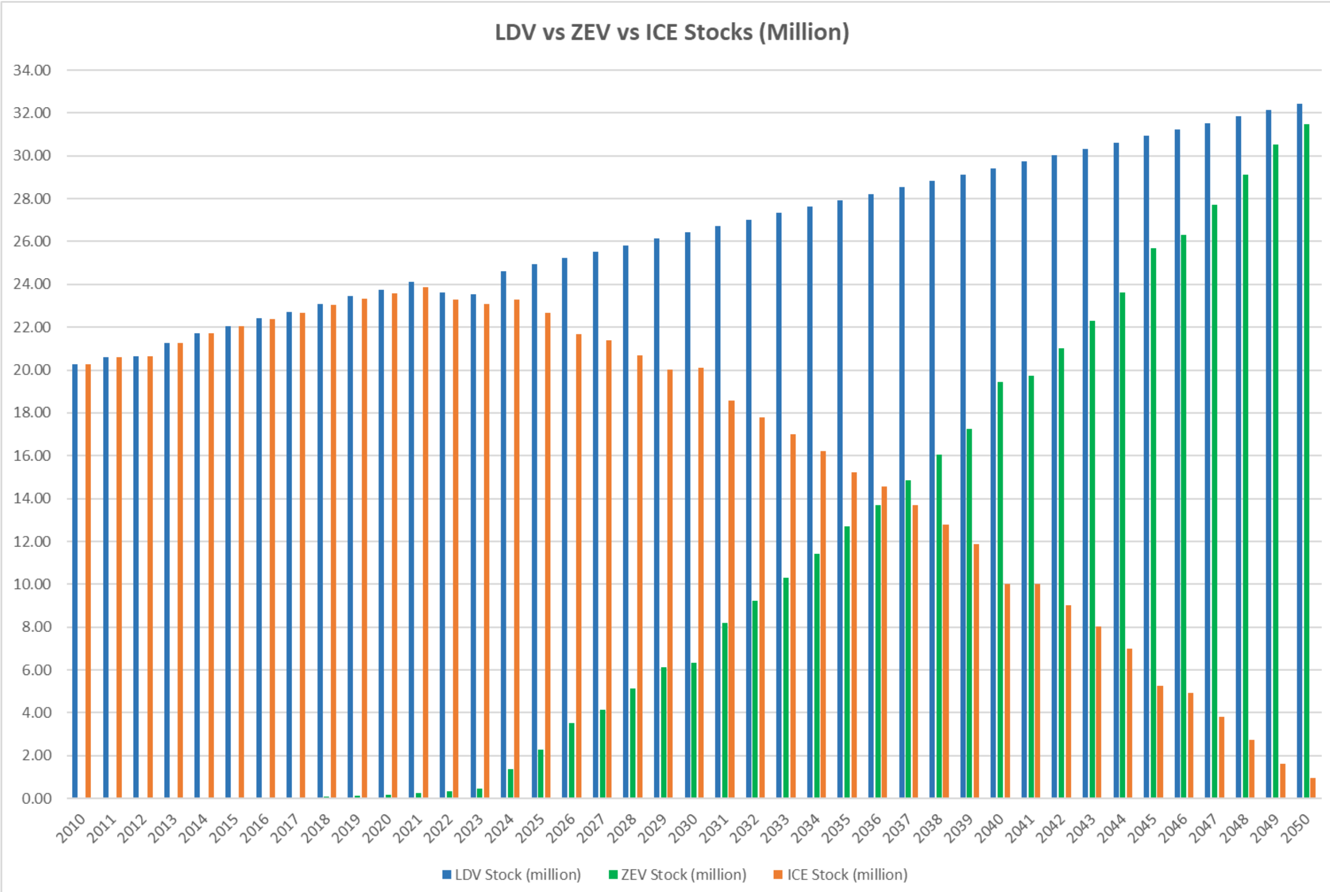

Figure 14 Projected trajectories of total LDV, ZEV, and ICE vehicle stocks in Canada, 2010–2050.

3.10 ICE Decline: Analysis & Implications for Gas Station Closures

As shown in the subsequent table, Canada's internal combustion engine (ICE) vehicle stock is projected to decline substantially between 2026 and 2050, falling from approximately 22 million vehicles to fewer than 2 million as zero-emission vehicles become dominant within the light-duty fleet. This sustained reduction in the ICE vehicle base implies a corresponding contraction in gasoline demand, which, under market-driven assumptions, is expected to induce progressive gasoline station closures over time. Closure impacts are modest in the early stages of the transition but could intensify in later decades, with the most critical period occurring **between approximately 2035 and 2045**, when reductions in refueling infrastructure may outpace the remaining spatial and operational needs of ICE users. This phase represents the greatest challenge for maintaining adequate fuel accessibility and motivates the need for targeted infrastructure and policy interventions.

The projected decline in internal combustion engine (ICE) vehicles implies a sustained reduction in gasoline demand, placing increasing economic pressure on the viability of retail fuel stations. By 2035, when ZEV vehicles are estimated to comprise approximately 46% of the light-duty vehicle stock, reduced throughput is expected to affect station profitability. This emerging vulnerability has been noted in public discourse, including a CBC News report highlighting uncertainty surrounding the long-term future of gasoline stations amid accelerating electric vehicle adoption [29].

Academic literature similarly suggests that, in the absence of adaptation strategies such as retrofitting stations for electric vehicle charging or alternative services, a substantial share of service stations may exit the market. Global estimates indicate that up to 25% of stations could close by 2035 under continued electrification trends [30]. In the Canadian context, these pressures are likely to be more pronounced in provinces experiencing rapid ZEV uptake and infrastructure expansion, such as British Columbia and Quebec. By 2050, with ICE vehicles projected to represent only a small residual share of the fleet, the gasoline refueling network may contract to a limited and **spatially uneven footprint**, raising the risk of localized “refueling deserts” and underscoring the need for proactive planning interventions during the transition period.

3.11 Gas Station Closures in Calgary

The transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs) under Canada’s Net-Zero ZEV mandate is expected to affect access to gasoline refueling infrastructure and urban travel patterns in Calgary. In this study, gasoline station closures are assumed to result from independent, market-driven decisions rather than coordinated policy actions and are represented analytically through randomized station removal **to reflect uncertainty** in closure locations. Closure levels for the Monte Carlo analysis are defined using fixed station-closure fractions aligned with the **Canada Energy Regulator’s** projected ZEV-stock milestones: 24% (2030), 46% (2035), 66% (2040), 83% (2045), and 95% (2050). These fixed fractions determine the number of stations removed in each simulated milestone year. and the associated decline in ICE vehicle stock and gasoline demand under the Net-Zero pathway.

3.12 Key Uncertainties

The linear regression-based projection of total LDV stock, and the inferred decline in ICE vehicles, assumes smooth long-term trends. Actual fleet evolution may diverge due to market saturation, macroeconomic shocks, behavioral shifts, or changes in travel demand (e.g., increased public transit use or shared mobility uptake). Regional heterogeneity also matters; Alberta's lower fuel prices and dispersed urban form may slow ZEV adoption and ICE retirement relative to provinces such as Quebec or British Columbia [31]. These factors introduce several key uncertainties that influence the accuracy, timing, and spatial distribution of the projected transition. The main sources of uncertainty include:

Mandate Implementation and Market Response:

The federal requirement for 100% ZEV sales by 2035 assumes full mandate compliance, adequate vehicle supply, and sustained consumer demand. Faster technological progress could push adoption above mandated targets, whereas supply-chain constraints, affordability challenges, or insufficient charging infrastructure could slow compliance. Delays in any of these factors would alter the timing and intensity of ICE fleet decline.

Global Market Dependencies:

Canada's ZEV trajectory is influenced by global automotive markets. Policy stringency in major regions (EU, United States, China) affects production allocation, model availability, and vehicle pricing. High global demand could temporarily restrict supply in Canada, introducing additional uncertainty in projected adoption rates.

Electricity Grid and Charging Infrastructure:

Full-scale ZEV adoption requires major upgrades to electricity generation, distribution capacity, and both public and private charging infrastructure. Delays in grid investment or charger deployment may constrain real-world adoption even under a binding sales mandate. Federal assessments indicate that tens of thousands of additional public chargers will be needed to support the projected ZEV fleet.

Policy Stability:

ZEV adoption is sensitive to the continuity of incentives and regulatory measures. Adjustments or temporary suspensions of programs such as the halt of the federal iZEV purchase incentive in early 2025 following fund depletion [26] may introduce short-term volatility in adoption rates. Such variability affects the precision of long-term projections.

Gasoline Station Closure Evidence:

Canada-specific empirical evidence on gasoline station closures during large-scale electrification is limited. As a result, this study infers closures from modeled gasoline-demand decline rather than direct observational data. This introduces **uncertainty in the timing and spatial pattern of station closures**, particularly in heterogeneous urban environments.

Overall, projections of ICE fleet decline and gasoline station contraction under the Net-Zero ZEV mandate contain structural uncertainty driven by technological adoption rates, policy implementation, economic conditions, and vehicle turnover dynamics. Data limitations and regional variability further constrain precision. Accordingly, results should be interpreted as indicative trajectories under the Net-Zero transition pathway rather than deterministic forecasts. Ongoing reassessment will be essential as empirical evidence on ZEV adoption and gasoline-station attrition becomes available.

3.13 Impact of ZEV Adoption on Gasoline Demand Reduction and Gas Station Closures in Canada (2025–2050)

Across Canada, service stations are predominantly privately operated; Natural Resources Canada reports that independent operators run 68% of service stations and set their own prices. [2] In Alberta specifically, fuel retailing is likewise a commercial, privately run market rather than a government-operated service, as Alberta's fuel-tax framework regulates registered fuel sellers (including retailers) that must comply with Alberta Tax and Revenue Administration requirements. (Government of Alberta). Therefore, the decline in the use of internal combustion engines (ICE) vehicles not only influences the composition of the vehicular fleet but also disrupts the established fuel economy of a network of **privately owned** gasoline stations. This section aims to derive potential trends in gas station closures based on projected EV adoption, providing a foundational basis for infrastructure planning, policy design, and strategic intervention. The business model of gas stations, largely dependent on consistent fuel demand, is highly sensitive to changes in fleet composition. As the number of ICE vehicles declines, so does the volume of fuel sales, the key revenue stream for gas station operators. As adoption accelerates, in the city, fuel stations that are already operating on narrow profit margins may find it unsustainable to continue unless they diversify or retrofit with EV charging options.

ZEV Stock Share vs. Gasoline Demand

To estimate gasoline demand reduction from rising ZEV stock, the approach used by the International Energy Agency (IEA) has been utilized. Following the IEA's Global EV Outlook methodology, we assume that the annual kilometers driven by EVs replace those that would otherwise have been covered by ICE vehicles. In other words, each additional EV on the road is presumed to displace an equivalent ICE vehicle's kilometers travelled. Using the stock-average fuel consumption of ICE vehicles, one can calculate the "fuel displaced" by the EV fleet. [32] Under these assumptions, the relationship between ZEV stock share and gasoline displacement is approximately linear. For instance, if 30% of cars are electric, they will eliminate roughly 30% of the gasoline that would have been used by a fully ICE fleet.

Many studies and policy reports emphasize that electric vehicles (EVs) exhibit substantially higher energy efficiency than internal combustion engine (ICE) vehicles, leading to reductions in overall fuel demand that exceed the direct displacement of gasoline consumption by ICEs. This effect is commonly assessed using a well-to-wheel (WTW) perspective, which accounts for energy conversion losses across the full supply chain and is widely applied in transportation energy analysis [33].

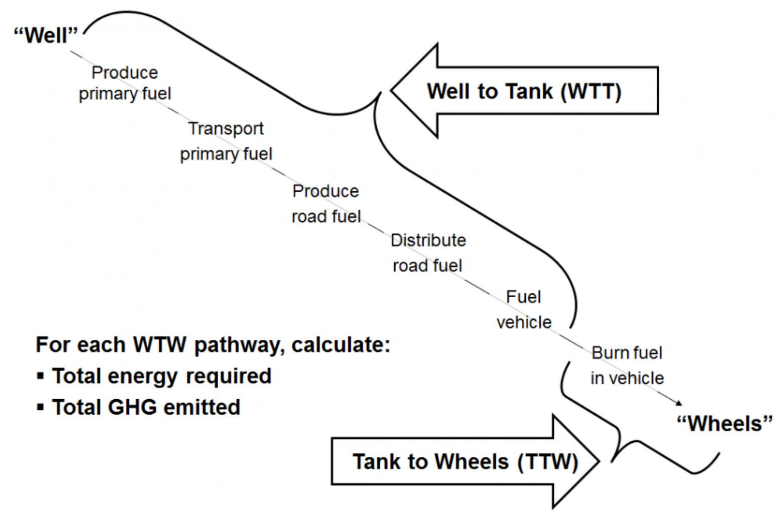

Figure 15 WTW analysis combines WTT and TTW emissions performance. (Image: EU Science Hub)

WTW comparisons consistently show that ICE vehicles achieve relatively low overall efficiencies, while EVs, particularly when supplied by low-carbon or renewable electricity, convert a much larger share of primary energy into useful vehicle motion. Reported WTW efficiencies range from approximately 11–27% for gasoline ICE vehicles, compared to 13–31% for EVs powered by natural-gas-based electricity and up to 40–70% for EVs supplied by renewable sources [34]. In parallel, remaining ICE vehicles are expected to achieve incremental efficiency improvements and increased use of biofuels over time, further moderating the overall decline in gasoline demand [28].

However, to maintain a conservative and transparent analytical framework aligned with the scope of this master's research, reductions in gasoline demand are modeled primarily as a linear function of the zero-emission vehicle (ZEV) share within the light-duty vehicle (LDV) fleet. Other influencing factors, including changes in vehicle-kilometers traveled, incremental improvements in ICE efficiency, and increased biofuel blending, are held constant. This simplification, consistent with modeling approaches used by the International Energy Agency, enables isolation of the direct effect of ZEV penetration on fossil fuel displacement while avoiding additional complications.

3.14 Modelling Assumptions

To operationalize the linear relationship between zero-emission vehicle (ZEV) penetration and gasoline demand reduction, and to translate projected demand decline into a tractable station-closure framework, the following assumptions are adopted. These assumptions are introduced to maintain analytical transparency, reproducibility, and consistency with the system-level scope of this study. The resulting outputs should therefore be interpreted as scenario-based estimates under explicit simplifying assumptions, rather than deterministic forecasts of future gasoline station closures:

Policy-Aligned Baseline Transition Pathway:

This thesis adopts a single policy-aligned ZEV adoption pathway as the baseline scenario for evaluating the implications of fuel-network contraction. The selected pathway reflects the national decarbonization direction and provides a policy-relevant reference case for infrastructure stress testing. However, it does not represent the full uncertainty range of future adoption trajectories. Slower adoption, delayed uptake, or more accelerated electrification could shift the timing and magnitude of gasoline demand decline and, consequently, the onset of refueling burdens. Alternative trajectories are therefore recognized as important extensions for future sensitivity analysis, but are not explicitly simulated in the present work.

Uniform Vehicle Usage:

ZEVs are assumed to be driven, on average, the same annual distance as the internal combustion engine (ICE) vehicles they replace. Although newer vehicles, often ZEVs in later years, may accumulate higher mileage, potentially displacing more fuel than implied by their stock share, this effect is neglected to maintain analytical simplicity.

Average Fuel Consumption:

According to the Canada Energy Regulator, the average fuel consumption of light-duty vehicles (LDVs) in Canada was approximately 8.9 L/100 km in 2017 [35]. For Alberta, a higher representative value of approximately 10 L/100 km is adopted, reflecting greater reliance on private vehicles and a higher prevalence of larger, less fuel-efficient SUVs and pickup trucks. Based on an average annual travel distance of approximately 15,000 km per vehicle, as reported in the NRCan Vehicle Survey [36], a typical LDV consumes on the order of 1,500 liters of gasoline per year. Consequently, each ZEV entering the fleet is assumed to offset approximately 1,500 liters of gasoline annually.

Constant Travel Demand:

Total vehicle-kilometers traveled are assumed to remain constant on a per-vehicle basis over time. In practice, population growth, economic activity, or rebound effects could increase travel demand, while mode shifts toward public transit or active transportation could reduce it. These effects are not modeled explicitly.

Proportional Gasoline-Demand Reduction:

Declines in gasoline consumption are assumed to be linearly proportional to the share of zero-emission vehicles (ZEVs) in the light-duty vehicle stock. Each percentage point increase in ZEV stock proportionally reduces aggregate gasoline demand. This simplification excludes non-linear effects such as preferential displacement of high-mileage drivers or accelerated turnover of older, less efficient ICE vehicles.

Constant Fleet Retirement Rate:

Vehicle retirement follows a stable, historically observed rate across all years of the projection. Neither policy-driven scrappage programs nor accelerated replacement due to technological advances are incorporated. As a result, the size and age composition of the ICE fleet decline gradually, reflecting typical turnover patterns rather than scenario-specific retirement shocks.

Linear Translation from Demand Reduction to Station Closures:

Projected gasoline station closures are represented using a proportional (linear) mapping between gasoline-demand reduction (and corresponding ICE decline) and the share of stations removed from the urban fuel network. This assumption is used to generate transparent milestone closure levels for network analysis. In practice, station exits may respond nonlinearly to demand decline due to threshold effects, local profitability conditions, lease constraints, competitive behavior, redevelopment pressure, and policy or business interventions. These effects are not modeled in the present framework.

Progressive Random Station Removals (Independent Closures):

Within the Monte Carlo simulation, station closures are modeled as progressive purely random removals, with stations treated as independently removable units under a given closure level. The removal of one station does not alter the probability of removal of adjacent or nearby stations. Accordingly, no explicit spatial autocorrelation, clustering, contagion effects, or market-dependency structure is imposed on the closure process. This assumption provides a neutral baseline stress-test of network vulnerability under generalized contraction, while avoiding additional market-behavior parameters that would require separate calibration.

Homogeneous Closure Likelihood Across the Study Area:

Closure probabilities are not differentiated by neighborhood-level demand, demographics, income, land use, regional EV uptake, station format, or local traffic intensity. All stations are treated uniformly within the simulated closure process at a given closure percentage. This assumption supports a first-order network accessibility analysis, but abstracts from spatially uneven transition dynamics and localized retail-market conditions that may influence real-world closure patterns.

No Behavioral Adaptation by ICE Drivers:

Internal combustion engine (ICE) drivers are assumed not to adjust their refueling behavior in response to declining station availability. Trip chaining, rerouting to minimize detours, reduced discretionary travel, or strategic refueling behavior are not modeled. This assumption isolates the structural impact of station closures on detour distances while excluding behavioral mitigation effects that could reduce real-world burdens.

Zero Gasoline Consumption by ZEVs:

ZEVs are assumed to consume no gasoline. Where plug-in hybrid vehicles are included within the ZEV category, their residual gasoline use is assumed to be negligible at the aggregate scale considered in this study.

Exclusion of Biofuel Effects:

The impact of ethanol or other biofuel blending is not explicitly modeled. Although federal regulations are expected to increase biofuel content in gasoline, thereby reducing petroleum-based fuel demand for remaining ICE vehicles [37], this study focuses on total gasoline consumption by LDVs. The additional displacement associated with biofuels lies outside the scope of the present analysis.

Under these assumptions, the ZEV stock share is translated into reductions in aggregate gasoline demand, and the resulting demand decline is used to construct proportional station-closure milestones for network contraction fractions. This structure serves as a first-order approximation that maintains analytical transparency and enables year-by-year estimation of fuel-network contraction consistent with the study's overall modeling framework. While simplified, the approach is suitable for identifying system-level refueling burden escalation and transition vulnerability under a clearly defined baseline scenario.

3.15 Projected Year-by-Year Reduction in LDV Gasoline Demand

As ZEVs become a larger share of the fleet, gasoline consumption by light-duty vehicles is expected to decrease essentially in proportion to the electric vehicle stock share. Below the ZEV stock projections are translated into estimated fuel demand reductions for each year 2030 through 2050. For context, the IEA's global modeling shows a similar trend: by 2030, the worldwide EV fleet is projected to displace over 5 million barrels of oil per day of road transport fuel (gasoline and diesel), up from 0.7 Mb/d (million barrels per day) displaced in 2022. [32] This equates to roughly a 10% reduction in global road-fuel demand by 2030 due to EVs, tracking closely with the global EV stock share rising into the teens by that time. Canada's scenario is even more aggressive in later years, given the push to 100% EV sales by 2035.

As gasoline consumption from passenger vehicles declines, fuel retailers face increasing financial pressure. This study assumes a **proportional relationship** between declining gasoline demand and the long-term reduction in operational gas stations. Under this assumption, a 30% drop in gasoline volume results in approximately 30% of stations becoming non-viable. This serves as a first-order approximation: in reality, closures would be uneven, with small or low-volume stations exiting first while larger stations may temporarily absorb a greater share of shrinking demand. Nonetheless, proportionality remains a reasonable basis for estimating long-horizon trends.

3.15.1 Historical context

Gas station networks have been contracting for decades due to improvements in fuel efficiency and evolving consumer behavior. In the United States, station counts fell by roughly 25% between 1994 and 2013, driven largely by reduced per-vehicle fuel consumption [38]. Fuel economy standards further suppressed demand in the 2010s, contributing to the exit of many marginal stations. Electrification is expected to intensify this pattern. A 2019 Boston Consulting Group analysis suggests that, under rapid electrification, up to 80% of fuel retail sites could become unprofitable by 2035, with even moderate scenarios producing widespread financial stress among traditional stations [39].

3.15.2 Alberta outlook

Alberta currently has roughly 3,000 retail fuel stations. Applying the linear decline assumption to projected reductions in LDV gasoline use suggests a substantial contraction in the provincial network. A 24% demand drop by 2030 would imply the closure or repurposing of roughly one-quarter of existing stations. By 2040, a 66% decline in gasoline volumes aligns with the loss of about two-thirds of stations. By 2050, with demand falling by more than 95%, only a small number on the order of 150 would remain in traditional form, primarily those located on major corridors or in areas with limited alternatives. Many existing sites would either shutter or transition toward other uses such as EV charging, hydrogen fueling, or general retail.

These estimates are illustrative, not predictive. Actual closures may occur more slowly if operators diversify revenue streams, or more quickly if EV adoption accelerates beyond current expectations. Policy interventions could also influence outcomes; this analysis assumes none. The simplified, proportional timeline summarized in Table 3 serves as a broad guide to the potential contraction of gasoline retail infrastructure under a sustained shift toward zero-emission mobility.

Table 3 Projected ZEV penetration and associated impacts on gasoline demand and gas stations in Canada's LDV sector (2030–2050)

Year	ZEV Stock Share	Fuel Demand Reduction	Gas Station Closures
2030	24.0%	~24% (≈1/4 less gasoline)	~24% closure (smaller sites)
2031	30.6%	~30%	~30%
2032	34.2%	~34%	~34%
2033	37.7%	~38%	~38%
2034	41.3%	~41%	~41%
2035	46%	~46%	~46%
2036	48.5%	~48%	~48%
2037	52.1%	~52%	~52%
2038	55.6%	~56%	~56%
2039	59.2%	~59%	~59%
2040	66.0%	~66% (≈2/3 less gasoline)	~66% (most rural stations gone)
2041	67.6%	~68%	~68%
2042	70.0%	~70%	~70%
2043	73.5%	~74%	~74%
2044	77.1%	~77%	~77%
2045	83.0%	~83%	~83%
2046	84.3%	~84%	~84%
2047	88%	~88%	~88%
2048	91.4%	~91%	~91%
2049	94.8%	~94%	~94%
2050	96.0%	~96% (virtually zero demand)	~95%

Note: *The ZEV stock share (percentage of LDVs that are electric) is based on Canada's mandated EV sales trajectory. Fuel demand reduction is assumed to be roughly equal to the fraction of the fleet that is ZEV. Gas station closures are assumed to be linearly proportional to the drop in gasoline volume. By 2050, gasoline use by cars is almost eliminated, implying over 95% of gas stations may close or transition away from selling gasoline.*

3.15.3 Key Milestones in Canada's LDV Gasoline Demand Trajectory and Station Closures

2030: Approximately 24% of Canada's light-duty vehicle (LDV) stock is projected to be ZEV by 2030. Under the proportionality assumption, this corresponds to a roughly **24% reduction in gasoline demand** relative to a no-EV baseline. With around 6.3 million ZEVs in a fleet of ~26.4 million vehicles, a substantial share of daily gasoline consumption is displaced. The remaining ICE fleet continues to dominate total fuel use, but ongoing improvements in fuel efficiency moderate the overall decline.

2035: By this point, **nearly half** (around 46%) of all LDVs on Canadian roads are expected to be zero-emissions. Gasoline demand from cars in 2035 would therefore be cut by roughly **46%** versus a no-EV scenario. Put differently, the LDV gasoline market is essentially half the size it would have been without electrification. This corresponds to the first year with 100% of new sales being ZEVs, so from 2035 onward the decline in fuel use will even accelerate as the last generation of gasoline cars ages out. The **crossover year** when EVs on the road outnumber ICE vehicles on the road is around 2037 in this scenario. At that point, almost half of all cars in Canada run on electricity, and gasoline demand falls below 50% of its peak.

2040: Approximately **66%** of the LDV fleet is ZEV by 2040, implying a **two-thirds reduction** in gasoline consumption from LDVs. Only one-third of cars still burn gasoline. It is likely that **gasoline demand for passenger transport in 2040 will be even less than one-third**, because in addition to 66% vehicles being electric, the remaining gasoline cars are more efficient and may be running on more environment-friendly fuel.

2050: By mid-century, Canada reaches **over 95% ZEV stock** in light-duty vehicles, virtually eliminating gasoline use in this sector. Proportionally, a **rough estimation of 95% reduction in LDV gasoline demand** is expected by 2050. The remaining ~3% of vehicles that are still ICE (perhaps ~1 million out of 32+ million) might be specialty or legacy vehicles (classic cars, rural/off-road trucks, etc.). These remaining ICE vehicles would account for a significantly small portion of the total miles driven, and they might use low-carbon biofuels or extremely efficient engines, so their gasoline consumption is minimal. In effect, **gasoline demand from passenger cars in 2050 is almost negligible**, on the order of just a few percent of today's volume. This represents a fundamental shift: gasoline, once the primary fuel for mobility, will have been mostly phased out from light-duty transportation.

3.23 Refueling Burden Metrics Under Random Gas Station Closures

As gasoline stations close, internal combustion engine (ICE) drivers must travel farther to reach remaining refueling points. This study quantifies these impacts using additional network distance as the primary measure of refueling burden. Detour distance offers a direct and transparent proxy for accessibility loss, incorporating the combined effects of extra travel time, route diversion, and added fuel use without requiring assumptions about value-of-time or price sensitivity. As station density declines, detours are expected to rise nonlinearly once spatial redundancy erodes.

To evaluate these conditions, the following operational metrics are defined:

3.23.1 Acceptable Refueling Detour Distance (ΔD^*) for ICE Vehicles in Urban Areas

Empirical evidence shows that urban gasoline drivers tolerate only modest deviations from their intended routes when refueling. Large datasets from North American fleets indicate average refueling deviations of approximately 2 miles (≈3.2 km), although these fleet datasets include both urban and between-city trips, meaning the 3.2 km figure reflects an upper bound because long-haul operations inflate average off-route distance [50]. Survey evidence likewise suggests that convenience, familiarity, and routine strongly shape refueling decisions, often outweighing marginal fuel-price differences [51]. High-resolution trajectory data, restricted to urban private-vehicle travel, confirm that median refueling detours are close to 1.2 minutes (≈1.6 km), with 75% remaining under 3 minutes, indicating substantially lower detour tolerance in typical urban conditions [52]. Drivers generally refuel at stations they already pass during routine travel.

Habitual travel-behavior literature reinforces this interpretation: disruptions to learned refueling patterns impose cognitive effort and reduce drivers' willingness to engage in additional route deviations [53]. These behavioral constraints become more pronounced as station availability declines.

Based on this evidence, this study adopts the following operational thresholds for interpreting urban refueling burdens:

- **≤0.6 km detour:** a conservative boundary representing typical "practical convenience," comparable to minor deviations embedded within dense urban travel patterns.
- **≈1.6 km detour:** an empirical threshold marking the upper limit of what most drivers tolerate as the Acceptable Refueling Detour Distance (ΔD*), beyond which accessibility becomes materially degraded.

These thresholds are not intended as universal behavioral limits, but as conservative and empirically grounded benchmarks for evaluating the resilience of urban refueling networks under progressive gasoline-station closures.

3.23.2 Mean Refueling Detour Distance

Mean refueling detour distance represents the mean additional network distance incurred when an ICE trip requires a refueling stop, relative to the direct origin–destination (O→D) route:

(Eq. 1) $$\Delta D = (O \rightarrow S \rightarrow D) - (O \rightarrow D)$$

where S denotes the station that minimizes the total refueling-constrained path d(O→S) + d(S→D) among all stations that remain open. Mean detour is obtained by averaging ΔD across all OD pairs with feasible refueling paths under a given station-closure scenario. All distances are measured along the road network.

3.23.3 Convenience Station Count (ConSC)

ConSC identifies the point at which station removals first begin to create noticeable inconvenience for ICE users. It is defined as the number of remaining stations at which the mean refueling detour first exceeds 0.6 km, rising from the typical baseline deviation (~0.2 km).

Although the network remains operationally functional at this stage, users begin to experience measurable inconvenience compared to normal refueling conditions.

3.23.4 Acceleration Station Count (ASC)

ASC marks the first point at which the detour curve shifts from slow, incremental increases to visibly faster growth. ASC is defined as the first closure level where the increase in mean detour between two consecutive closure levels is substantially larger than the early-stage increments. This metric captures the onset of system strain, indicating when the refueling network begins to degrade more quickly even though detours may still remain below the allowable threshold.

Operationally, ASC is detected from the slope/curvature table. Because curvature represents the change in slope (i.e., acceleration of the detour growth), ASC is identified as the first closure level where curvature exceeds an early-stage noise threshold and does so persistently (curvature ≥ 0.05 m per removed station for 2 consecutive closures compared to early stage values of below 0.03). This persistence rule prevents false ASC detections caused by isolated fluctuations and ensures ASC marks a genuine regime shift from gradual degradation to accelerating network deterioration.

3.23.5 Critical Station Count (CSC)

CSC represents the point at which refueling accessibility becomes operationally unacceptable. It is defined as the number of remaining stations at which the mean refueling detour first exceeds the allowable detour threshold (ΔD^*) of 1.6 km.

Beyond this point, even one additional station closure pushes the average user beyond empirically supported tolerances. CSC therefore reflects the minimum number of stations required to maintain acceptable refueling accessibility for urban ICE users.

3.24 Projected Refueling Detours Under a Fixed Allowable Threshold

In the current urban context, gasoline refueling imposes almost no additional travel burden: empirical observations show that near-route refueling deviations are extremely small, typically on the order of 0.2 km, due to the high density and spatial redundancy of existing stations.

Behavioral research provides insight into how drivers respond when familiar refueling patterns are disrupted. Studies indicate that perceived inconvenience rises as infrastructure thins, prompting drivers to pay greater attention to station availability and location [54]. Broader travel-behavior literature further shows that such adjustments unfold gradually and are often triggered by breaks in established routines [55], [56]. These perspectives offer contextual understanding of how real-world drivers might adapt as stations become scarcer.

However, this thesis does not model adaptive behavior. For methodological clarity and strict comparability across Monte Carlo closure levels, refueling accessibility is evaluated against a fixed allowable detour threshold of 1.6 km, consistent with empirical evidence indicating that typical urban refueling detours fall within approximately 1–2 km for most drivers [50], [52]. Thus, a ΔD^* = 1.6 km threshold is adopted as a conservative operational benchmark.

Accordingly, results in this study should be interpreted as the performance of the shrinking refueling network relative to this fixed benchmark, using the contrast between Calgary's current negligible detours (≈0.2 km) and rising simulated values as a consistent indicator of network strain under progressive station closures.

3.25 Plausibility and Scope of the Threshold Model

The fixed detour threshold adopted in this study serves as an operational benchmark for interpreting simulated refueling burdens under progressive reductions in gasoline-station availability. A constant acceptability limit, ΔD^*, is applied uniformly across all Monte Carlo closure levels and milestone years to classify modeled outcomes. This benchmark is not intended to represent a universal behavioral limit for all drivers; rather, it provides a consistent evaluative reference against which the performance of the shrinking fuel network can be compared.

The rationale for applying a fixed ΔD^* is grounded in the structure of the refueling problem. As stations close, the feasible set of O→S→D paths contracts, mechanically increasing minimum refueling distances for affected origin–destination pairs. When the modeled detour exceeds the ΔD^* threshold, this signals that the fuel network has entered a regime where the remaining station configuration imposes burdens beyond the adopted tolerance level. Exceedances therefore serve as objective indicators of accessibility degradation driven by infrastructure scarcity rather than behavioral assumptions.

The scope of this threshold framework is intentionally limited. The ΔD^* value is not derived from stated-preference estimation, econometric refueling-choice models, or detailed behavioral calibration. It functions instead as an interpretive tool that ensures comparability across closure sequences, facilitating identification of the closure levels at which the fuel network ceases to provide acceptable accessibility for urban ICE users.

To test the robustness of modeled accessibility impacts, detour statistics are reported using both unweighted and trip-weighted aggregation (Eq. 2 and Eq. 3). Agreement between these metrics strengthens confidence that the network's performance is not an artifact of OD distribution alone, while divergence highlights that high-demand corridors experience systematically different burdens under infrastructure contraction.

(Eq. 2) $$D_{0,u} = \left(\frac{1}{M}\right) \sum_{i=1}^{M} D_i$$

(Eq. 3) $$D_{0,w} = \frac{\sum_{i=1}^{M} w_i D_i}{\sum_{i=1}^{M} w_i}$$

where$D_{0,u}$ is the unweighted mean detour across all origin-destination (OD) pairs, $D_{0,w}$ is the trip-weighted mean detour, D_i is the detour value for OD pair i, w_i is the number of trips (or trip demand) associated with OD pair i, and M is the total number of OD pairs included in the analysis.

3.26 Summary

This chapter presented the analytical and computational framework used to quantify refueling accessibility under progressive gasoline-station closures. The approach integrates ArcGIS-based network-distance computation, Monte Carlo random-closure simulation, and analytically reconstructed O→S→D paths using fixed cost matrices. Key evaluation metrics, including mean detour distance, the Critical Station Count (CSC), Acceleration Station Count (ASC), and the fixed allowable detour threshold ΔD*, were defined to assess how fuel-network performance changes as station density declines.

These components together provide a consistent basis for interpreting refueling burden across closure levels. The next chapter applies this framework to Calgary, presenting simulated detour increase, threshold exceedances, and the onset and critical stage of refueling network degradation across milestone years.

CHAPTER 4: REFUELING DETOURS UNDER PROGRESSIVE RANDOM CLOSURES

This chapter evaluates refueling detours for ICE trips in Calgary under progressive, randomly simulated gasoline-station closures. The analysis includes only trips whose origins and destinations fall within the defined Calgary study boundary.

Refueling burden is measured using the detour metric ΔD introduced in Chapter 3 (Eq. 1). Monte Carlo station-removal experiments simulate closure trajectories, with refueling-route selection and closure-milestone mapping. Results are interpreted using the two thresholds established earlier: a convenience level of ~0.6 km and an allowable detour threshold $\Delta D^* = 1.6$ km. The Critical Station Count (CSC) is the station count at which mean detour first exceeds ΔD^*, indicating that the urban fueling network becomes operationally inadequate.

4.1 Urban Trip Data and Study Area

This study evaluates intra-urban trips whose origins and destinations fall within the municipal boundary of the City of Calgary. OD pairs were derived from provincial Transportation Analysis Zone (TAZ) data and filtered to retain only trips fully contained within the Calgary boundary. Zone centroids were used as analysis points, consistent with the structure of the source dataset.

All gasoline stations inside Calgary were included as candidate refueling locations. To avoid boundary artifacts and represent realistic near-edge refueling, stations within a 10 km buffer of the municipal boundary were also included.

4.2 Network Analysis and Cost Matrix Creation

Road-network distances were computed using ArcGIS Pro's Network Analyst extension, automated in Python (ArcPy) to (i) select city-specific origins/destinations (TAZ centroids) and candidate fuel stations using a city-boundary buffer, (ii) generate explicit many-to-many OD "known-pairs" tables for Origin→Station and Station→Destination links, and (iii) solve both link sets at scale using the Large Network Analysis Tools with chunked, multi-process execution, exporting the resulting OG and GD route distances for downstream analysis. All origins, destinations, and stations (as defined in Section 4.1) were located onto the network. The OD, OS, and SD cost Matrices were then extracted from the three separate network analyses to generate three fixed distance tables:

- direct O→D distances
- origin-to-station (O→S) distances
- station-to-destination (S→D) distances

The O→S and S→D tables were then merged to construct a complete candidate O–S–D cost matrix for each OD pair, where total refueling-path cost is given by the shortest of (O→S) + (S→D). Stations were ranked for every OD pair according to this combined cost, producing a deterministic, precomputed station-ranking list for all the OD pairs.

These preprocessed tables form the fixed inputs to the Monte Carlo simulation. During simulation, the refueling-constrained distance for each OD pair is obtained by scanning its ranked station list and selecting the minimum O→S→D path among the stations that remain open at each closure step, eliminating the need for repeated network computations.

4.3 Monte Carlo Simulation of Progressive Random Station Closures

To represent progressive but uncertain station closures, a Monte Carlo station-removal simulation was implemented. The simulation generates many random closure sequences (uniform sampling without replacement) and evaluates refueling burden metrics after successive removals using precomputed network distance tables derived from OD Cost Matrix solves in ArcGIS Pro Network Analyst. Across all experiments, the origin–destination set and OD network distances are held fixed; only the set of available refueling stations changes with each removal step.

With numerous stations within the city, the number of possible station-closure configurations at a given closure fraction is combinatorically large, making exhaustive evaluation infeasible. Randomized station-removal experiments therefore provide a tractable means of sampling plausible remaining-station configurations at each closure stage. By evaluating refueling detours across many realizations, the analysis estimates the expected detour increase, variability, and tail-risk behavior at each milestone closure level, rather than relying on a single deterministic closure path.

4.3.1 Implementation

Due to the massive size of the whole network, a comparatively large number of Monte Carlo iterations was required to produce statistically defensible estimates of refueling detours and station-level importance. However, each iteration is computationally intensive because the simulation must update the refueling distance for every OD pair at every station-removal step using multi-gigabyte cost-matrix tables. On the available hardware (Intel Core i7 12700h with 12 cores), a full 20,000-round batch required approximately five days of continuous parallel processing, imposing a practical upper limit on the feasible number of iterations.

Lower round counts (<3000) exhibited noticeable variability in both the trip-weighted mean detours and the identity of high-impact ("critical") stations. As the number of rounds increased, these fluctuations diminished substantially. A run-count stability assessment (next subsection) showed that key outputs stabilized well around 15000 rounds; nevertheless, 20,000 rounds were carried out to further reduce Monte Carlo sampling noise and improve the robustness of station-importance rankings.

Each Monte Carlo run begins with the full candidate station set defined in the study area. Stations are removed one at a time through uniform random sampling without replacement, generating a progressive closure trajectory. At each removal step, the simulation evaluates the refueling-route distance for every OD movement by selecting the shortest feasible path that includes exactly one remaining station. This distance is then computed using the precomputed network-distance tables from

the ArcGIS analysis:

Eq. 4 $$d_{ij}^{stop} = \min_{(k \in S)}\left(d_{ik} + d_{kj}\right)$$

Where:

$i = origin\ zone\ index$

$j = destination\ zone\ index$

$k = gas\ station\ index$

$S = set\ of\ available\ stations\ at\ the\ current\ closure\ step$

$d_{ik} = shortest\ road\ distance\ from\ origin\ i\ to\ station\ k$

$d_{kj} = shortest\ road\ distance\ from\ station\ k\ to\ destination\ j$

$d_{ij}^{stop} = shortest\ road\ distance\ from\ origin\ i\ to\ destination\ j\ with\ one\ refueling\ stop$

To align stochastic closure trajectories with milestone years, each milestone closure fraction is converted to a station-removal count k_Y (Eq. 5). For each run, the aggregated metrics are extracted exactly at the milestone removal count, creating a one-to-one correspondence between (i) milestone closure levels and (ii) distributions of simulated outcomes across many random closure orders. These milestone distributions are subsequently compared against the thresholds to determine whether the remaining refueling network remains adequate under plausible random closure sequences.

To extract results at milestones, each milestone closure fraction is converted into an integer station-removal count based on the initial number of candidate stations. The ceiling operator is used because the product of the milestone closure fraction and the initial station count may not be an integer, while the removal count must be an integer.

Eq. 5 $$k_Y = \lceil p_Y \cdot N \rceil$$

Where:

$Y = milestone\ year$

$p_Y = closure\ fraction\ assigned\ to\ year\ Y$

$N = initial\ number\ of\ available\ gasoline\ stations\ in\ the\ study\ (city\ limits +\ buffer)$

$k_Y = number\ of\ stations\ removed\ by\ milestone\ year\ Y$

At each removal level, refueling-burden metrics are extracted as (i) the unweighted mean detour distance and (ii) the trip-weighted mean detour distance across OD pairs, together with a band indicator defined as the trip-weighted 95th and 5th percentiles (band between P95 and P05). Maximum (worst-case) detours are not used because they are highly sensitive to outliers and do not provide a stable representation of network performance under stochastic closure sequences.

By extracting metrics exactly at the milestone removal count k_Y, a direct correspondence is established between stochastic closure realizations and policy-relevant milestone years. This enables consistent evaluation of whether the remaining refueling network at each stage can accommodate ICE travel without imposing unacceptable inconvenience.

At each milestone year, simulated detours are compared against the acceptability benchmark defined in Chapter 3 ($\Delta D^* = 1.6$ km). If the trip-weighted mean detour exceeds ΔD^* at a given milestone, the refueling network is interpreted as broadly inadequate under typical conditions. If the mean remains below ΔD^* while the trip-weighted P95 exceeds ΔD^*, the network is interpreted as conditionally adequate on average but vulnerable to high-burden outcomes under plausible closure sequences.

4.3.2 Run-Count Stability Assessment

A run-count stability assessment was conducted to determine the number of Monte Carlo iterations required for statistically reliable outputs. At each 1,000-run increment, an independently sampled subset was drawn uniformly from the full 20,000 runbank, and all detour and station-importance metrics were recomputed using only the selected runs. Independent random subsets were used at each increment and across replicates to avoid any dependence on temporal ordering within the runbank.

Stability was evaluated using two quantitative criteria, selected to capture both global changes in network burden and local changes in station-level influence:

- **Milestone trip-weighted mean detours**
    - Calculated at the designated closure milestones (2025–2050).
    - Stability tolerance**:** absolute change ≤ 0.010 km between successive increments.
    - Purpose: verifies that the aggregate detour trajectory is not sensitive to Monte Carlo sampling depth.
- **Top-100 station-importance set**
    - Defined as the 100 stations with the highest average marginal detour impact.
    - Stability tolerance: Jaccard similarity ≥ 0.90 between successive increments.
    - **Jaccard similarity**: $J(A, B) = |A \cap B|/|A \cup B|$ for two sets of A and B is defined as the ratio of the size of their intersection to the size of their union quantifying the consistency of important stations identification.

Run-count stability was assessed using a criterion applied to successive-checkpoint changes. For detour stability at the 2050 milestone, the absolute change relative to the previous checkpoint was computed and the relevant curve was drawn; the stable run count was defined as the first checkpoint after which the curve remained at or below the tolerance of 0.010 km. For Top-100 station set stability, Jaccard similarity between successive checkpoints was computed; the stable was defined analogously as the first checkpoint after which the curve remained at or above the 0.90 threshold. A complete run-count stability diagnostic table is provided in Appendix B (Table B.1).

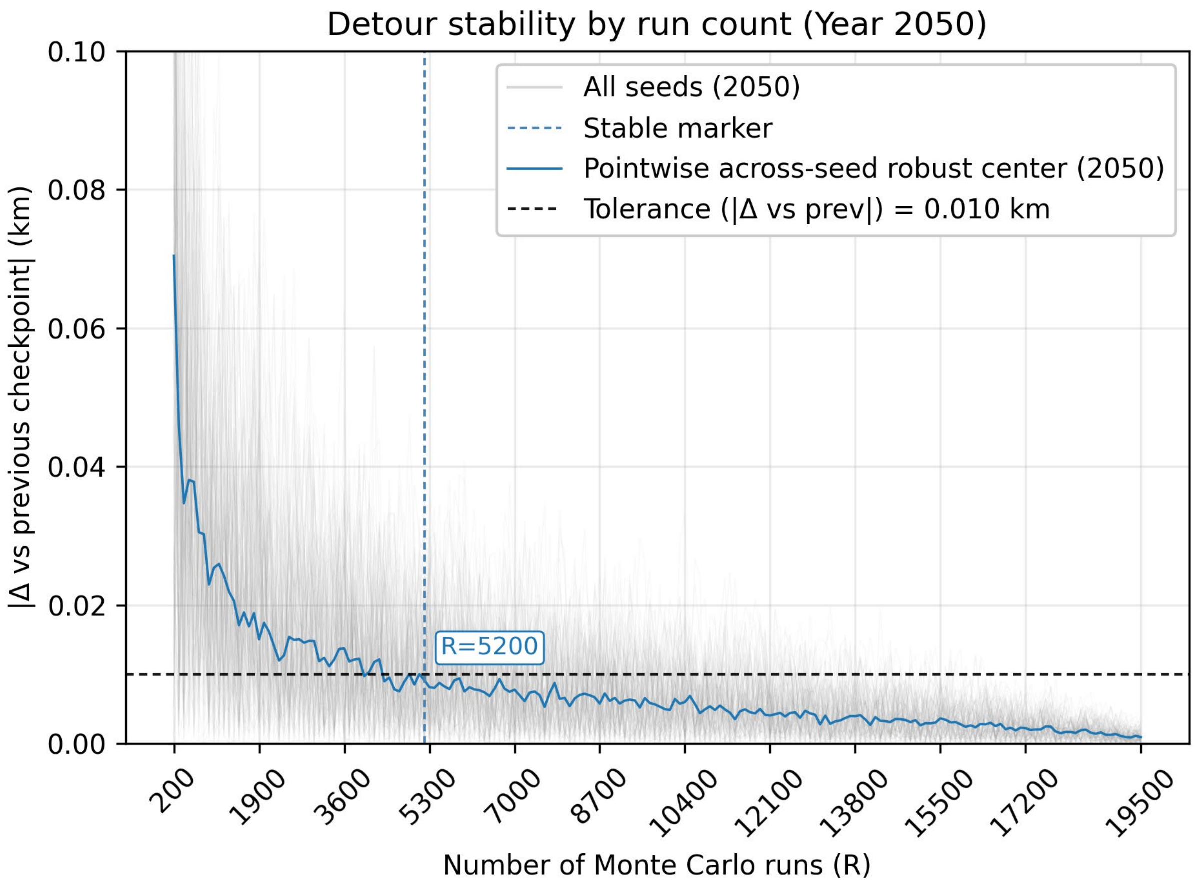

Figure 16 Detour stability versus run count at the 2050 milestone

Absolute change in the detour metric relative to the previous checkpoint is shown as a function of Monte Carlo run count R. Thin grey lines represent seed-level trajectories; the solid line is the pointwise cross-seed robust center (median across seeds at each R). The horizontal dashed line indicates the tolerance (0.010 km). The vertical dashed line marks the earliest stable run count R^*, defined as the first checkpoint after which the robust-center never exceeds the tolerance.

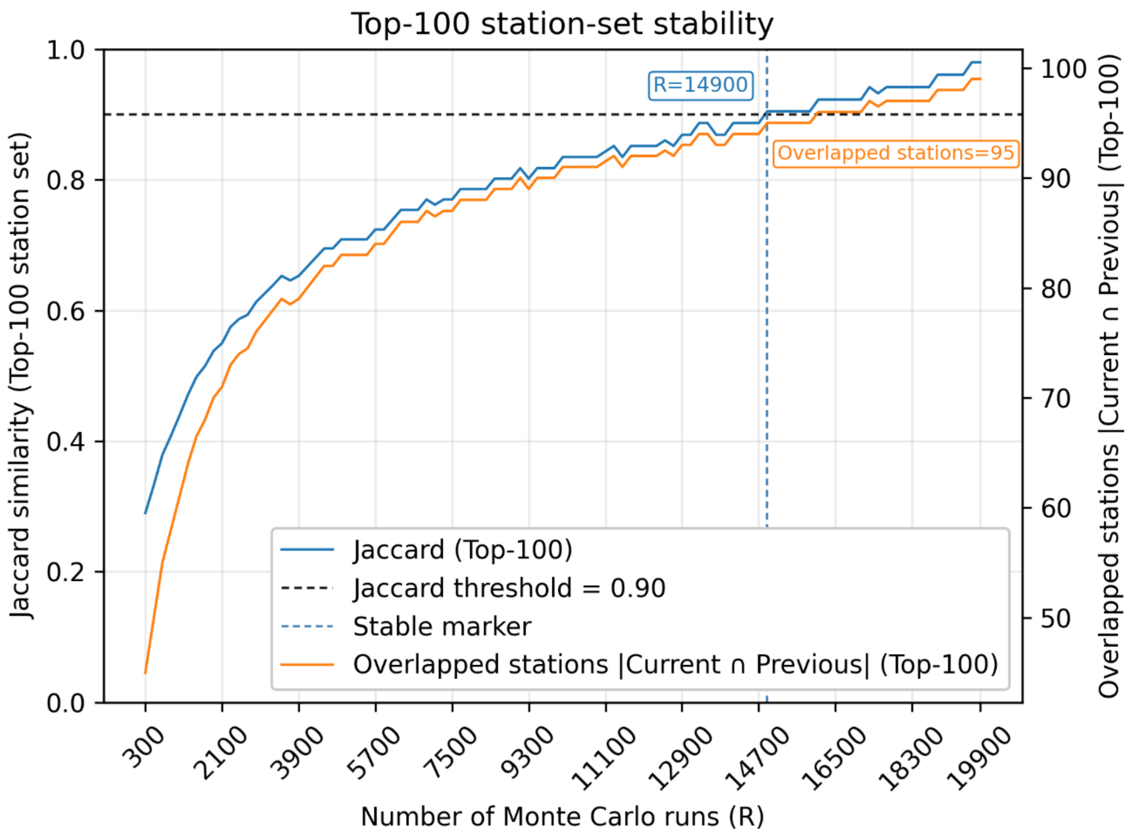

Figure 17 Top-100 station-set stability versus run count (absorbing criterion)

Jaccard similarity (the solid blue line) between successive checkpoints for the Top-100 station set is shown as a function of R (left axis), with the corresponding overlap count |Current ∩ Previous| (the orange solid line) on the right axis. The horizontal dashed line indicates the Jaccard threshold (0.90). The vertical dashed line marks the earliest stable run count R*, defined as the first checkpoint after which the robust-center never falls below the threshold.

4.4 Results: Refueling Detour Outcomes Under Progressive Station Closures

This section presents the refueling detour outcomes produced by the Monte Carlo station-closure simulations, focusing on how refueling burden evolves as gasoline station availability declines at predefined milestone closure levels.

4.4.1 Summary of Milestone Closures

The station-closure milestones used in the Monte Carlo simulations represent **predefined closure fractions** applied to the initial Calgary candidate-station set (stations inside the municipal boundary plus the 10 km buffer). These milestones are not intended to predict which or when specific stations will close. Instead, they provide **policy-relevant reference points** for evaluating how refueling detours evolve as the gasoline-station network contracts under an adoption-driven demand-decline assumption.

For each milestone year Y, a closure fraction p_Y is specified and converted to an integer removal count $k_Y = \lceil p_Y \cdot N \rceil$, where N is the initial number of candidate stations. The simulation then evaluates detour metrics immediately after the removal of k_Y stations, ensuring a direct mapping between milestone years and the stochastic station-removal trajectories.

Table 4 Station-Closure Milestones Adopted for the Calgary Case Study

Year	ZEV Stock Share	ICE Vehicle Stock (estimated)	Gasoline Station Network Status	Modeling note (as used in simulation)
2030	~24%	~20 million	Early contraction	Remove $k_{2030} = \lceil 0.24N \rceil$ evaluate detours across Monte Carlo runs; Marginal and low-throughput stations begin exiting the market.
2035	~46%	~15 million	Noticeable decline	Remove $k_{2035} = \lceil 0.46N \rceil$ evaluate detours across Monte Carlo runs; Marginal and low-throughput stations begin exiting the market. Economic pressure intensifies; hybrid stations and selective closures could become more common.
2040	~66%	~10 million	Rapid contraction	Remove $k_{2040} = \lceil 0.66N \rceil$; spatial coverage becomes sensitive to closure ordering; Marginal and low-throughput stations begin exiting the market.
2045	~83%	~6 million	Severely reduced	Remove $k_{2045} = \lceil 0.83N \rceil$; remaining-station configurations drive high detour variability.
2050	~95%	~1.3 million	Minimal, residual network	Remove $k_{2050} = \lceil 0.95N \rceil$; evaluate detours under extreme scarcity conditions. Representing the terminal phase of the gasoline refueling system.

NOTE: *The ZEV stock shares are provided as* ***context*** *for the long-run transition pathway and the associated* *demand-decline narrative. In the Calgary simulations, the operative inputs are the* ***modeled closure fractions*** $\mathbf{p_Y}$ *applied to the Calgary candidate-station set; the Monte Carlo procedure does not use national ICE stock counts and does not attempt to forecast specific station closures.*

Following this summary, Figure 18 provides an initial, high-level visualization of the full detour trajectory across the entire closure pathway. The figure shows the mean detour curves (weighted and unweighted) accompanied by a set of sampled Monte Carlo realizations, offering an intuitive overview of how refueling burden grows as stations are progressively removed. Detailed milestone-specific statistics, threshold comparisons (ΔD*), uncertainty bands, and variability analyses are presented in the next section **(4.4.2)**.

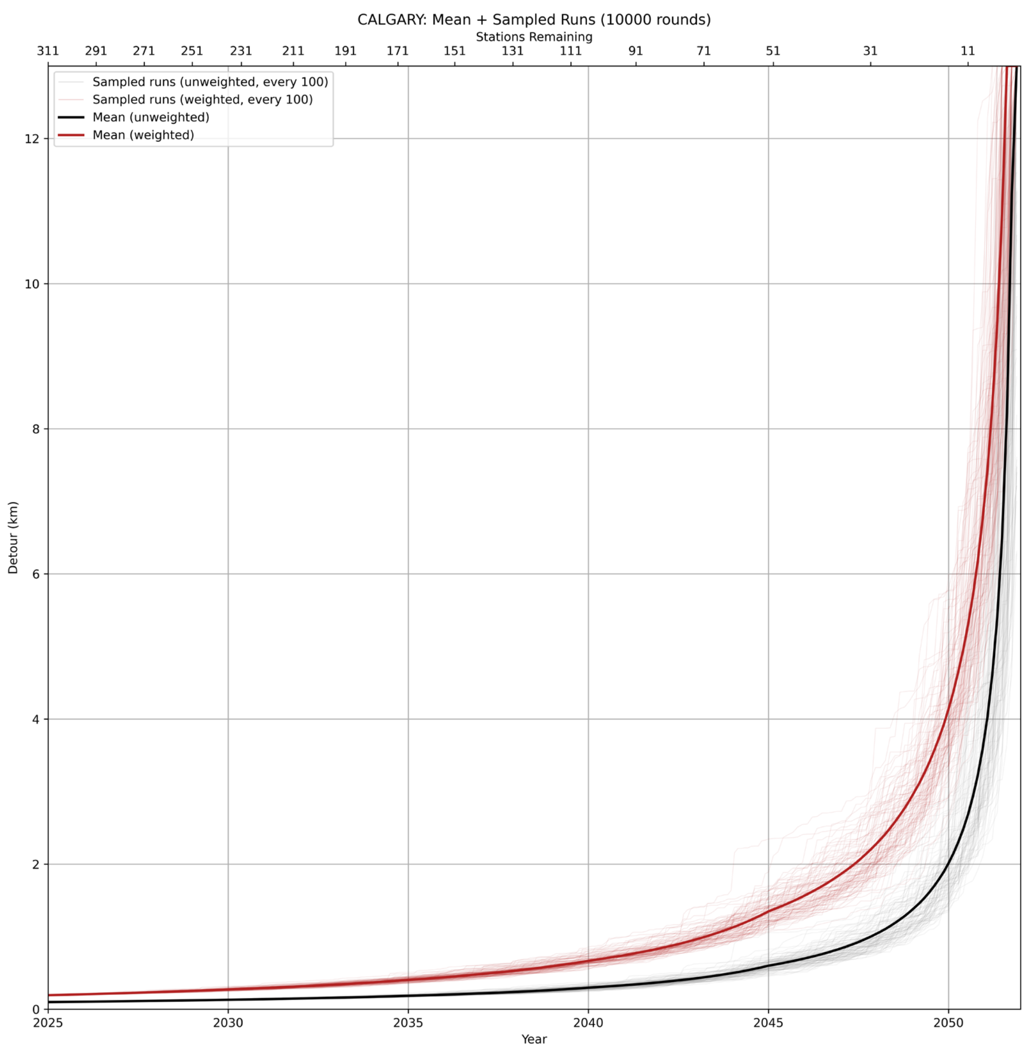

Figure 18 Mean Refueling Detour Trajectory and Sampled Monte Carlo Realizations for Calgary (2025–2050)

Note. *Figure 18 provides a high-level overview of the refueling detour trajectory as stations are progressively removed. The black and red curves show the unweighted and trip-weighted mean detours across all Monte Carlo runs, while the light gray and light red lines represent sampled individual realizations of the closure process.*

4.4.2 Aggregate Refueling Detour Metrics at Milestone Years

This subsection reports the aggregate refueling-detour outcomes extracted at each milestone closure level defined in Table 4. All results are derived directly from the Monte Carlo simulation outputs and the post-processing implemented in *Python*. The analysis focuses exclusively on the detour distance metric ΔD, consistent with the behavioral benchmark ΔD* = 1.6 km adopted in Chapter 3.

At each milestone year, the simulation provides the following key indicators:

1. **Mean trip-weighted detour (ΔD_w):**

   The average additional distance incurred when refueling is required, computed across all origin–destination pairs using trip weights. This is the primary metric for evaluating network-level refueling burden. These values correspond to Weighted Mean Detour in *Milestone Metrics* table (Table 5) and the labeled milestone markers in the mean detour (Fig 19) plot.

2. **Mean unweighted detour (ΔD_u):**

   The simple arithmetic average of detours across all OD pairs. This metric is included for completeness and as a check on whether trip-weight patterns materially influence the burden estimates.

3. **Run-level uncertainty band (P05–P95 of mean detour curves):**

   At each milestone, the simulation aggregates thousands of random closure sequences. For each sequence, a mean detour curve is produced, and the collection of these curves yields a distribution at every closure level. The P05–P95 interval of this distribution is plotted as the blue band in the detour MC plot (Fig 19) and is exported per milestone as

- RunBand_P05_MeanDetour_Weighted
- RunBand_P95_MeanDetour_Weighted.

These values quantify the stochastic variability induced by random closure orderings.

4. **Comparison to the acceptable detour threshold (ΔD* = 1.6 km):**

The constant allowable threshold is superimposed on the detour MC plot (green dashed line) and is included in the milestone table as the Allowable Detour. Two conditions are evaluated:

(i) whether the Weighted Mean Detour (km) exceeds the allowable threshold ΔD*, and
(ii) whether the Weighted Mean Detour P95 (km) exceeds ΔD*.

These are reported in the milestone table under "Exceeds Threshold (Mean)" and "Exceeds Threshold (P95)".

Exceedance of ΔD* by the mean detour indicates broad inadequacy of the remaining network, while exceedance only in the P95 metric indicates increasing vulnerability to unfavorable closure patterns.

These metrics together provide a comprehensive view of the evolving refueling burden at each milestone year. The detour MC plot presents the trajectory of mean detours and uncertainty, while the accompanying *enhanced_milestone_metrics.csv* file summarizes numerical milestone values used in Chapter 5 for interpretation and policy assessment.

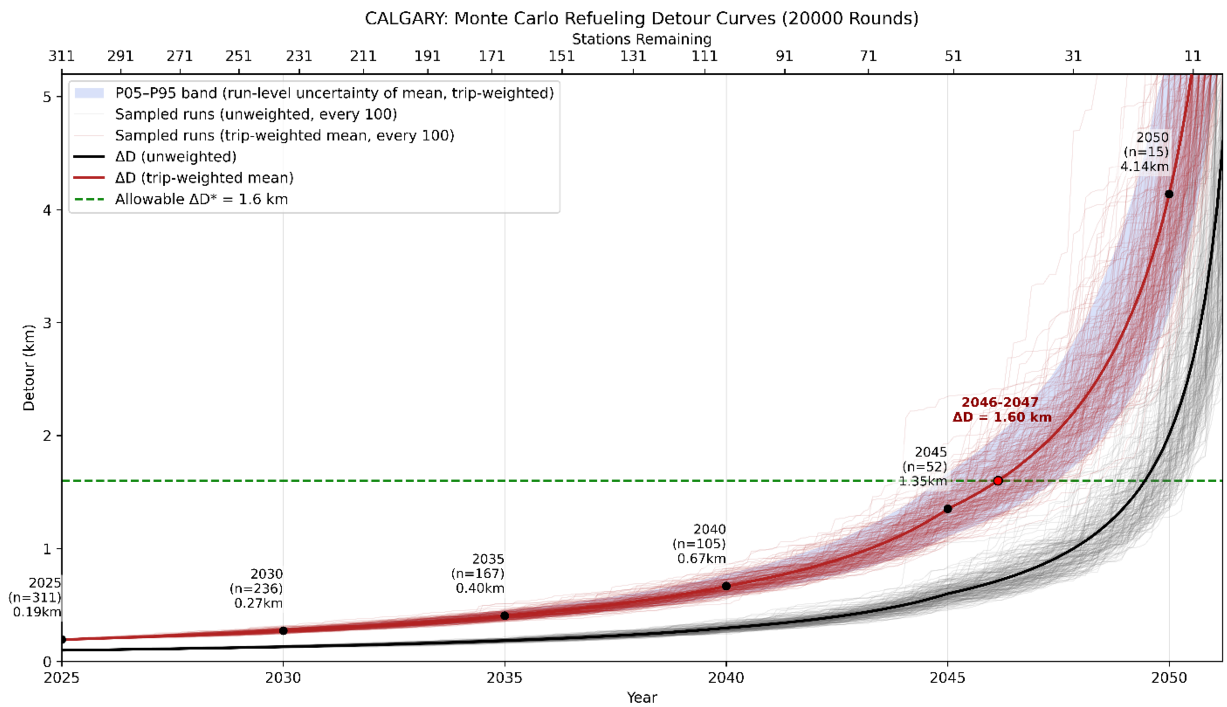

Figure 19 Monte Carlo refueling detour evolution with ΔD = 1.6 km and milestone markers*

Table 5 Milestone refueling detour metrics for Calgary under progressive random station closures. Values summarize Monte Carlo outcomes at fixed closure levels and do not represent forecasts of individual station closures.

City	**CALGARY (20000 rounds)**					
Year	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Closure Fraction	0	0.24	0.46	0.66	0.83	0.95
Stations Removed	0	75	144	206	259	296
Stations Remaining	311	236	167	105	52	15
D_0 (km)	8.19	8.19	8.19	8.19	8.19	8.19
ΔD_0 (km)	0.1938	0.1938	0.1938	0.1938	0.1938	0.1938
Weighted Mean Detour (km)	0.1938	0.2721	0.4048	0.6675	1.3493	4.1379
Weighted Mean Detour P05 (km)	0.1938	0.2531	0.3646	0.5811	1.1072	3.0943
Weighted Mean Detour P95 (km)	0.1938	0.2944	0.453	0.776	1.6674	5.6235
Trip-Weighted P50 (km)	0.01	0.0475	0.1257	0.2745	0.6182	2.6437
Trip-Weighted P75 (km)	0.23	0.3289	0.4817	0.8268	1.7809	6.2178
Trip-Weighted P95 (km)	0.98	1.2835	1.7608	2.8219	5.2473	13.1046
Exceeds Threshold (Mean)	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE
Exceeds Threshold (P95)	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE

The Calgary results show that refueling detours remain very small through 2035, even after nearly half of stations are removed. Up to this point, the weighted mean detour stays well below 0.5 km, and neither the mean nor the run-level P95 values approach the 1.6 km threshold.

By 2040, with about 66% of stations removed, the mean detour increases to about 0.67 km, and the spread between P05 and P95 widens, indicating growing variability across different closure sequences. However, the system as a whole still remains within acceptable limits.

A clear shift appears at 2045. Although the weighted mean detour is still below the threshold, the run-level P95 exceeds 1.6 km, showing that unfavorable closure orderings can already produce great strain in parts of the network even though average conditions remain acceptable.

By 2050, the system crosses into general inadequacy: the mean detour exceeds 4 km and the P95 surpasses 5.6 km. At this stage, the remaining fuel network is too sparse to provide convenient refueling for most ICE users.

4.4.3 Markers Along the Detour-Closure Trajectory (ConSC, ASC, CSC)

This subsection reframes the results for further analysis of Calgary's refueling network under progressive station closures. Instead of reporting only milestone-year detour levels, the three transition markers from the trip-weighted mean detour curve are extracted. Each marker captures a different way the system becomes sensitive as redundancy is removed.

ASC (Acceleration Station Count) is the earliest marker and occurs at $k = 140$ removed stations (171 remaining) around year ≈ 2034, where the weighted mean detour is 0.3943 km. ASC is not a detour-threshold crossing; it is a slope-based change point, meaning it detects when additional closures start producing persistently larger marginal increases in detour compared with the early-closure baseline. Its early appearance indicates that Calgary's network begins losing meaningful redundancy before detours become visibly high, i.e., the system's sensitivity (derivative) increases while the absolute burden is still moderate.

ConSC (Convenience Station Count) occurs later, at the first crossing of the inconvenience threshold $\Delta D = 0.6$ km, at $k = 195$ removed (116 remaining) around year ≈ 2039, with weighted mean detour 0.6012 km. ConSC represents the point where the average user-level burden becomes noticeable in magnitude, implying that the remaining spatial coverage is no longer sufficient to keep detours consistently small across the network.

CSC (Critical Station Count) is reached at the first crossing of the allowable detour limit ΔD* = 1.6 km, at k = 268 removed (43 remaining) around year ≈ 2046, with weighted mean detour 1.6218 km. This marks the transition into a regime where the refueling network, on average, exceeds the adopted serviceability threshold, meaning that the remaining stations are too few and/or too poorly distributed to maintain acceptable accessibility.

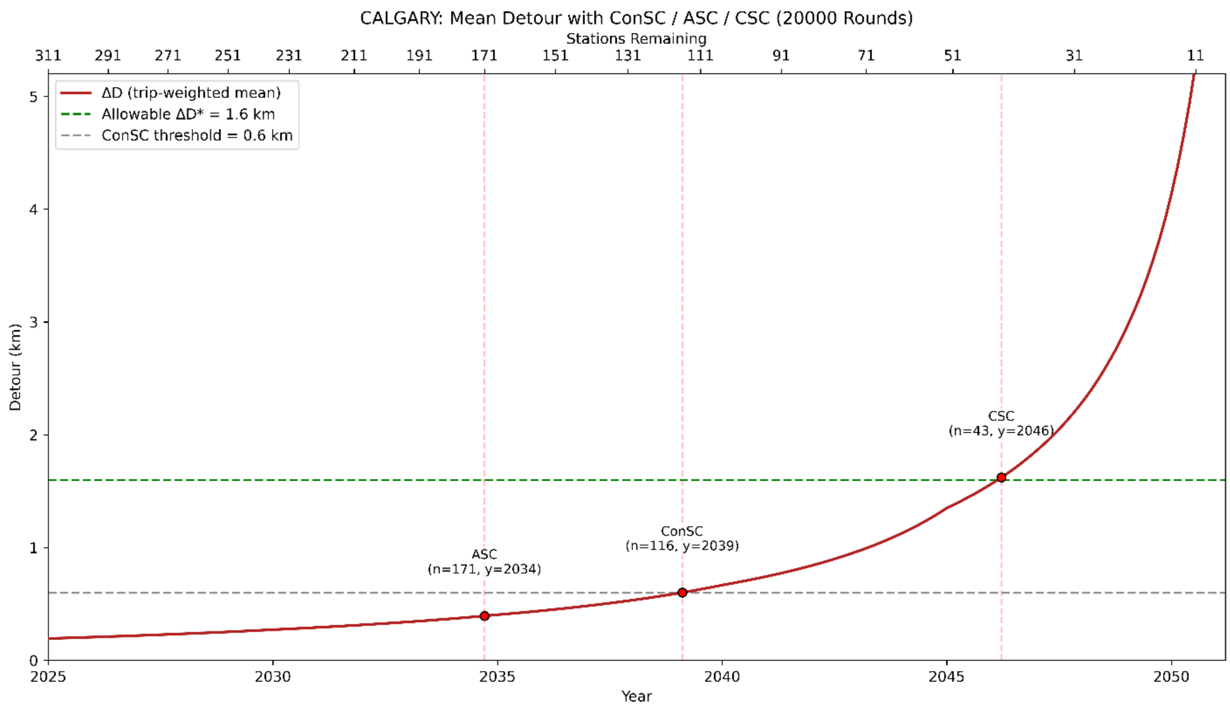

Figure 20 Mean detour curve with ASC, ConSC, and CSC markers (trip-weighted)

Taken together, these markers describe a three-stage sensitivity progression: (1) latent sensitivity growth (ASC) where the network begins to "stiffen" against closures even while detours are still low; (2) practical inconvenience onset (ConSC) where burden becomes materially noticeable; and (3) threshold exceedance (CSC) where the system crosses the defined performance limit. This adds diagnostic value beyond milestone reporting because it identifies where the curve behavior changes, not only what detour happens to be at preselected closure fractions.

4.4.4 Identification of the Critical Transition Zones

A transition zone emerges when detours are assessed against the constant acceptable limit (ΔD* = 1.6 km) and the three sensitivity markers (ASC, ConSC, CSC). The early milestones (2030–2035) remain well below ΔD* for both the trip-weighted mean and P95, indicating a resilient network. The ASC point (near 2035; k=140, n=171) shows sensitivity starts accelerating even while detours are still modest. The ConSC point (~2039; k=195, n=116) marks the first crossing of 0.6 km mean detour, signaling reduced redundancy and noticeable inconvenience. While 2040 averages remain below ΔD*, dispersion increases and outcomes become more configuration-dependent. The CSC point (~2046; k=268, n=43) is the first crossing of ΔD* on the mean curve; beyond this (consistent with 2045–2050), the network becomes broadly inadequate across closure orders.

Interpretation by milestone:

2030–2035 (Stable Zone):
Trip-weighted mean detours remain low (≈0.27–0.40 km) and far below ΔD*, with narrow uncertainty bands. The ASC point (~2034.7) indicates that sensitivity (rate of deterioration) begins increasing near the end of this interval, but the network still performs comfortably.

~2039–2040 (Emerging Transition / Convenience Loss):
The ConSC point (~2039.11) marks the first crossing of 0.6 km mean detour, indicating a shift from "robust" to "inconvenience-prone" behavior. By 2040, the mean is still below ΔD*, but dispersion increases and some realizations approach higher-burden outcomes, resilience becomes increasingly configuration-dependent.

2045–2050 (Inadequate Zone):
Detours become structurally high and increasingly unavoidable across closure orders. The CSC point (~2046.2) provides a curve-based confirmation of this regime change by identifying the first crossing of ΔD* on the mean curve. This aligns with the milestone pattern where late-stage closures produce unacceptable burdens even under favorable sequences.

4.4.5 Slope and Curvature of the Mean Detour Trajectory

The slope and curvature of the mean trip-weighted detour curve provide additional insight into how the refueling network responds to sequential station closures. The slope measures the marginal increase in mean detour for each additional station removed, while the curvature reflects the acceleration of detour growth and highlights nonlinear sensitivity regions. The corresponding plots are shown in Fig. 21 (Slope) and Fig. 22 (Curvature), and the full k-resolved numerical values used to generate these figures are reported in Appendix Table A-1.

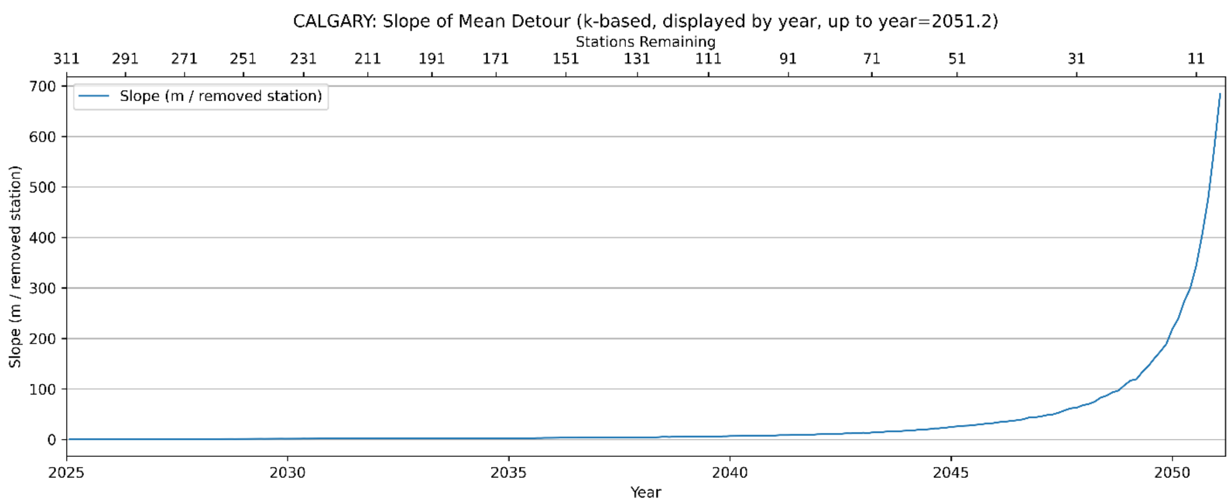

Figure 21 (Slope)

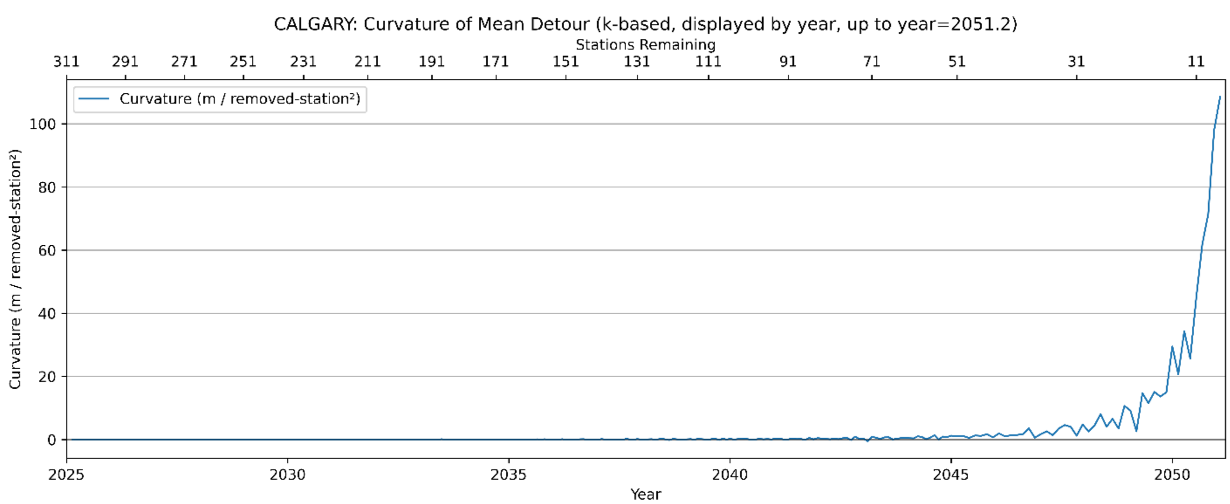

Figure 22 (Curvature)

The curvature plot reinforces this behavior. Curvature remains close to zero through **2030–2035** (e.g., 0.012 at 2030; −0.012 at 2035), consistent with a mostly linear, stable response. Curvature becomes distinctly positive by **2040** (≈0.215), signaling the onset of accelerating detour growth. This acceleration intensifies by **2045** (≈1.219) and becomes dominant by **2050** (≈29.46), revealing a sharp upward inflection in the detour trajectory as spatial redundancy in the refueling network disappears.

Together, the slope and curvature results in Fig. 21 and 22 corroborate the conclusions of Section 4.4.4: the system remains relatively stable through **2035**, becomes **marginal and increasingly sensitive** around **2040**, and enters a **critical, unstable regime** beyond **2045**, where additional closures produce disproportionate increases in refueling detours.

4.5 Synthesis and Interpretation of Network Degradation

This section integrates the empirical findings from Sections 4.4.2_4.4.5 into a coherent interpretation of how Calgary's gasoline refueling network degrades under progressive station closures. The focus shifts from reporting numerical outcomes to explaining their operational meaning, interpreting them relative to the acceptability thresholds defined in Chapter 3, and outlining the implications for a managed transition toward widespread zero-emission vehicle adoption.

4.5.1 Synthesis of Network Degradation Regimes

Across all Monte Carlo realizations, Calgary's gasoline refueling network exhibits a consistent three-regime degradation structure that reflects the interplay between redundancy, station configuration, and nonlinear detour escalation:

Redundancy-Dominated Regime (≤2035):
High spatial coverage ensures multiple viable stations per origin. Closure order has negligible influence. Detours increase nearly linearly, slope remains low, and curvature stays near zero—indicating stable incremental deterioration.

Configuration-Sensitive Regime (≈2040):
Redundancy drops enough that which stations remain matters more than how many remain.

Detour variability widens, marginal impacts (slope) increase, and curvature shows a distinct upward shift. The network becomes structurally sensitive to losing the wrong stations.

Fragility-Driven Regime (≥2045):
The network enters a nonlinear acceleration zone. The slope plot shows large marginal impacts per additional closure, while the curvature plot peaks sharply, indicating the onset of accelerated burden growth.

Refueling outcomes diverge widely across closure sequences, and even optimistic sequences produce high detours. This synthesis provides the conceptual backbone for interpreting system behavior and aligns directly with the milestone metrics, slope/curvature patterns, and uncertainty signatures observed in Section 4.4.

4.5.2 Planning Implications for a Managed Transition

The shift from redundancy to fragility has practical implications for managing the decline of gasoline refueling infrastructure during Alberta's transition to ZEVs:

- **Unmanaged, market-driven closures pose significant risk after 2040.**
  The system becomes highly sensitive to which stations close rather than how many. Random exit can trigger premature local fuel-access failures.
- **Strategically preserving or retrofitting a small number of high-impact stations can delay system fragility.**
  The slope and curvature results reveal that only a limited set of stations drive the nonlinear acceleration zone. Maintaining service at these locations stabilizes the system disproportionately.
- **Hybrid or dual-fuel stations may be needed during the 2040–2045 interval.**
  Even moderate shifts in network geometry during this period can create unreliable accessibility for ICE users who remain in the fleet.
- **Planning efforts should target the configuration-sensitive zone, not the early or late regimes.**
  Before 2035, intervention is unnecessary; after 2045, the system is already unstable. The window for impact is the mid-transition.

These insights form the technical foundation for the policy recommendations discussed in Chapter 5.

4.5.3 Transferability of the Calgary Case Study

While Calgary's street layout, travel patterns, and station distribution are unique, several structural findings are transferable to other urban areas with dispersed, auto-dependent networks:

- **The three-regime degradation structure is general.**
  Most cities with grid-like arterial patterns and moderate station density will experience a similar transition from redundancy → sensitivity → fragility.
- **Threshold-year locations are city-specific, but threshold mechanisms are not.**
  Exact years depend on adoption scenarios, but the emergence of a configuration-sensitive zone is a structural property of refueling networks.
- **Nonlinear deterioration driven by loss of key stations is universal.**
  The curvature peaks are not a Calgary artifact; they reflect spatial dependency inherent to refueling networks.

However, density-rich cities (e.g. Toronto core) may experience later transition points due to higher station concentration.

4.5.4 Limitations and Scope

The analysis relies on several necessary simplifications:

- **Closure order is modeled in a purely random manner**, representing uncoordinated exits but not strategic withdrawals by fuel suppliers. In other words, the simulation treats station loss as a stochastic contraction process rather than a business-decision process. This allows the analysis to test network vulnerability under generalized decline, but it does not capture targeted market behavior such as firms preferentially closing low-profit sites, consolidating geographically, or preserving flagship/high-volume stations.
- **Station closures are treated as independent events**, such that the removal of one station does not change the likelihood of closure of adjacent or nearby stations. As a result, spatial autocorrelation, clustering, and localized contagion effects in station exits are not explicitly

represented. In practice, nearby stations may share similar demand conditions, redevelopment pressures, or competitive dynamics, which can produce clustered closures or spatial dependence over time. These local interdependencies are intentionally excluded in the present baseline framework.

- **Closure likelihood is treated as homogeneous across the study area**, without conditioning on neighborhood demand, demographics, income, land use, regional EV uptake, or station-specific commercial characteristics. This means that, at a given closure level, all stations are treated as equally likely to be removed in the simulation. The assumption supports a first-order system-level analysis of network accessibility, but it abstracts from real-world spatial unevenness in transition dynamics and retail viability.
- **Travel demand is assumed static**, without behavioral rerouting, time-of-day effects, or induced demand. The analysis therefore evaluates detour impacts under a fixed trip pattern rather than a dynamically adapting travel system. In reality, drivers may adjust trip timing, combine trips, change destinations, or alter travel frequency in response to changing refueling convenience, which could either mitigate or amplify observed detour burdens.
- **Charging infrastructure growth is not explicitly modeled**, though it indirectly drives gasoline demand decline. The study captures the transition effect primarily through ZEV adoption and the associated reduction in gasoline demand, rather than through a spatially explicit simulation of charger deployment and charging accessibility. As a result, interactions between charging-network expansion, travel behavior, and localized fuel-demand shifts are not represented directly.
- **Drivers are assumed to refuel at the minimum-detour station**, without modeling preferences, brand loyalty, or price sensitivity. This assumption provides a consistent accessibility-based estimate of refueling burden by isolating the geometric/network effect of station loss. However, actual driver choices may reflect station familiarity, fuel price differences, amenities, queueing conditions, perceived safety, or habitual routing, which can produce refueling behavior that deviates from the minimum-detour option.

These limitations do not undermine the central conclusions, but they bound interpretation to the modeled conditions and to a baseline framework under progressive random station removals. Accordingly, the results should be interpreted as scenario-based estimates of refueling burden and network vulnerability, rather than deterministic forecasts of the exact timing or spatial pattern of future station closures. Real-world outcomes may be more spatially uneven or clustered, which could affect the absolute magnitude and timing of detour impacts.

Section 4.5 synthesized the simulation outcomes into distinct degradation regimes, linking threshold exceedance, sensitivity to closure order, and nonlinear detour growth to the progressive loss of refueling network redundancy. While this synthesis clarifies when and how the gasoline refueling network in Calgary becomes vulnerable, the results also raise broader questions regarding planning responses, policy timing, and the management of infrastructure decline during the transition toward zero-emission vehicles. These questions are addressed in Chapter 5.

CHAPTER 5: DISCUSSION AND PLANNING IMPLICATIONS

5.1 Overview and Purpose of the Discussion

Chapter 4 quantified how refueling detours evolve in Calgary as gasoline stations are progressively removed under ZEV-driven demand decline. Using network analysis, Monte Carlo simulation, and derivative indicators (slope and curvature), the results revealed nonlinear deterioration patterns and a clear transition from redundancy to fragility.

The purpose of Chapter 5 is to interpret them in three ways:

1. **Behavioral interpretation** relative to the threshold detour ΔD^*,
2. **Structural interpretation** of refueling network degradation mechanisms,
3. **Planning interpretation** relevant to managing the gasoline network during the ZEV transition.

This chapter answers the central question left open by Chapter 4:

When does the gasoline refueling network stop functioning acceptably, why does it fail in that way, and what does that imply for infrastructure planning during the transition period?

5.2 Interpretation Relative to Acceptability Thresholds

The behavioral limit of ΔD* = 1.6 km provides a clear reference for interpreting the operational significance of the simulated detour outcomes. Unlike relative metrics or trend-only comparisons, ΔD* allows the identification of functional adequacy, incipient vulnerability, and systemic inadequacy. To complement this threshold view, the other three curve-based markers (ASC, ConSC, CSC) were utilized to indicate when sensitivity begins to accelerate (ASC), when noticeable inconvenience emerges (ConSC), and when the mean response crosses the acceptable limit (CSC).

5.2.1 Adequate Operation (≤ 2035)

Up to the 2035 milestone, both the mean trip-weighted detour and its uncertainty envelope remain well below ΔD*. Refueling inconvenience is low, consistent across Monte Carlo realizations, and largely insensitive to closure order. This is also consistent with the ASC marker occurring around 2034 (k = 140 removed; n = 171 remaining), indicating that marginal sensitivity begins to accelerate near the end of the "adequate" period even though absolute detour levels remain modest (~0.39 km at ASC). From an operational standpoint, the network functions normally: drivers experience minor additional travel and no meaningful accessibility constraints emerge.

5.2.2 Emerging Vulnerability (≈ 2040)

At the 2040 milestone, mean detours remain acceptable, but the upper tail of the distribution moves closer to ΔD*. This corresponds to a shift in how the system degrades: performance becomes increasingly dependent on which stations remain rather than station count alone. The transition is reinforced by the ConSC marker occurring around 2039 (k = 195; n = 116), where the trip-weighted mean detour first exceeds 0.6 km (~0.60 km), indicating the onset of noticeable inconvenience and reduced redundancy. The network is still mostly functional, but no longer robust to arbitrary closure sequences.

5.2.3 Operational Inadequacy (≥ 2045)

By 2045, the trip-weighted P95 detour exceeds ΔD*, implying that a substantial share of ICE trips already experience refueling deviations beyond the adopted tolerance level. The transition to systematic inadequacy is anchored by the CSC marker at approximately 2046 ($k = 268$; $n = 43$), where the trip-weighted mean detour first exceeds ΔD^* (~1.62 km). By 2050, even the mean detour rises well above ΔD^*, demonstrating that burdensome detours are no longer tail outcomes but the prevailing network condition. This stage reflects structural failure of the gasoline refueling network well before total station disappearance, when the remaining network cannot provide functionally acceptable access for routine urban refueling.

5.3 Structural Interpretation of Network Degradation

Beyond threshold exceedance, the simulations clarify *how* and *why* refueling networks deteriorate as stations close. Early closures eliminate mostly redundant stations, producing small and nearly linear increases in detour because multiple alternative refueling paths remain available. As redundancy erodes, the network becomes configuration-dependent: accessibility hinges increasingly on the presence or absence of a small number of strategically positioned stations. This shift, visible in the widening Monte Carlo bands, rising slope, and non-zero curvature, marks the structural transition from stable to fragile behavior. Once it occurs, additional closures trigger disproportionately large detour increases not due to station count alone, but because critical spatial linkages have been lost, driving the nonlinear degradation seen at later milestones.

5.3.1 Redundancy Collapse and Configuration Sensitivity

In the early stages, several stations serve each region, so individual closures produce minimal disruption. As closures accumulate, this redundancy collapses unevenly across the city. Stations located near major corridors, intersections, or spatial bottlenecks become disproportionately influential: their loss reshapes refueling paths for many OD pairs. This is why two Monte Carlo realizations with the same number of remaining stations can exhibit dramatically different detour patterns, the system has shifted from density-driven to configuration-driven behavior.

5.3.2 Nonlinear Escalation Captured by Slope and Curvature

The slope and curvature of the mean detour curve reveal the onset of nonlinear degradation:

- Low slope and near-zero curvature correspond to predictable, linear deterioration in the redundancy-dominated regime.

- Rising slope and positive curvature signal accelerating burden as key structural stations are lost.

The pronounced curvature rise between the 2040 and 2045 closure levels confirms that detours do not increase smoothly; they escalate sharply once the network loses critical spatial anchors. This nonlinearity is not a modeling artifact but an inherent structural property of spatial service networks.

5.4 Implications for Managing the Gasoline Network During Transition

The results show that uncoordinated random closures can destabilize the refueling network once closure levels approach mid-transition. After this point, outcomes depend more on which stations remain than on total station count, indicating a need for coordinated planning to maintain basic fuel accessibility during the transition period.

5.4.1 Unmanaged Closure Is Risky

Once the network moves beyond its redundancy-dominated phase, random closures introduce structural risks that are not visible when looking only at the overall number of stations. Random withdrawals can:

1. **Produce localized fueling deserts early**, even while the city still has dozens of stations overall, simply because a few spatially strategic locations disappear;
2. **Trigger steep increases in refueling detour**, as shown by the rising slope and curvature patterns once the system enters the configuration-sensitive regime;
3. **Eliminate predictability for ICE users**, since refueling burden depends heavily on closure order rather than closure fraction.

These failures could emerge well before the network reaches what would be considered a “low-density” state, meaning that relying solely on market forces would allow instability to appear long before urban planners and decision makers expect it.

5.4.2 Strategic Value of High-Impact Stations

The detour, slope, and curvature plots (Figures 19–22) show that refueling network degradation is not driven uniformly by all station closures. Once the system enters the configuration-sensitive and fragility-dominated regimes, a relatively small subset of stations exerts a disproportionate influence on overall performance.

This transition is consistent with the curve-based sensitivity markers. The acceleration point (ASC) occurs around 2034 ($k = 140$ removed; 171 remaining), indicating that marginal detour begins to accelerate even while absolute detour levels remain modest. The system becomes materially configuration-sensitive by the noticeable inconvenience onset (ConSC) at 2039 ($k = 195$ removed; 116 remaining; $\Delta D \approx 0.60$ km), and it reaches systematic inadequacy at the critical threshold crossing (CSC) around 2046 ($k = 268$ removed; 43 remaining; $\Delta D \approx 1.62$ km). In these regimes, outcomes are increasingly governed by which structurally influential stations survive rather than by station count alone.

Figure 23 presents the Top-100 high-impact stations, ranked by their average marginal detour impact across the Monte Carlo ensemble, with impacts interpreted most strongly in the post-ASC and post-ConSC regime where configuration dominates. The distribution clearly demonstrates that a small number of stations serve as structural anchors: their removal produces substantially higher increases in trip-weighted detour than the removal of the remaining majority. This reinforces the finding that spatial configuration, not simple station count, is responsible for the onset of nonlinear degradation.

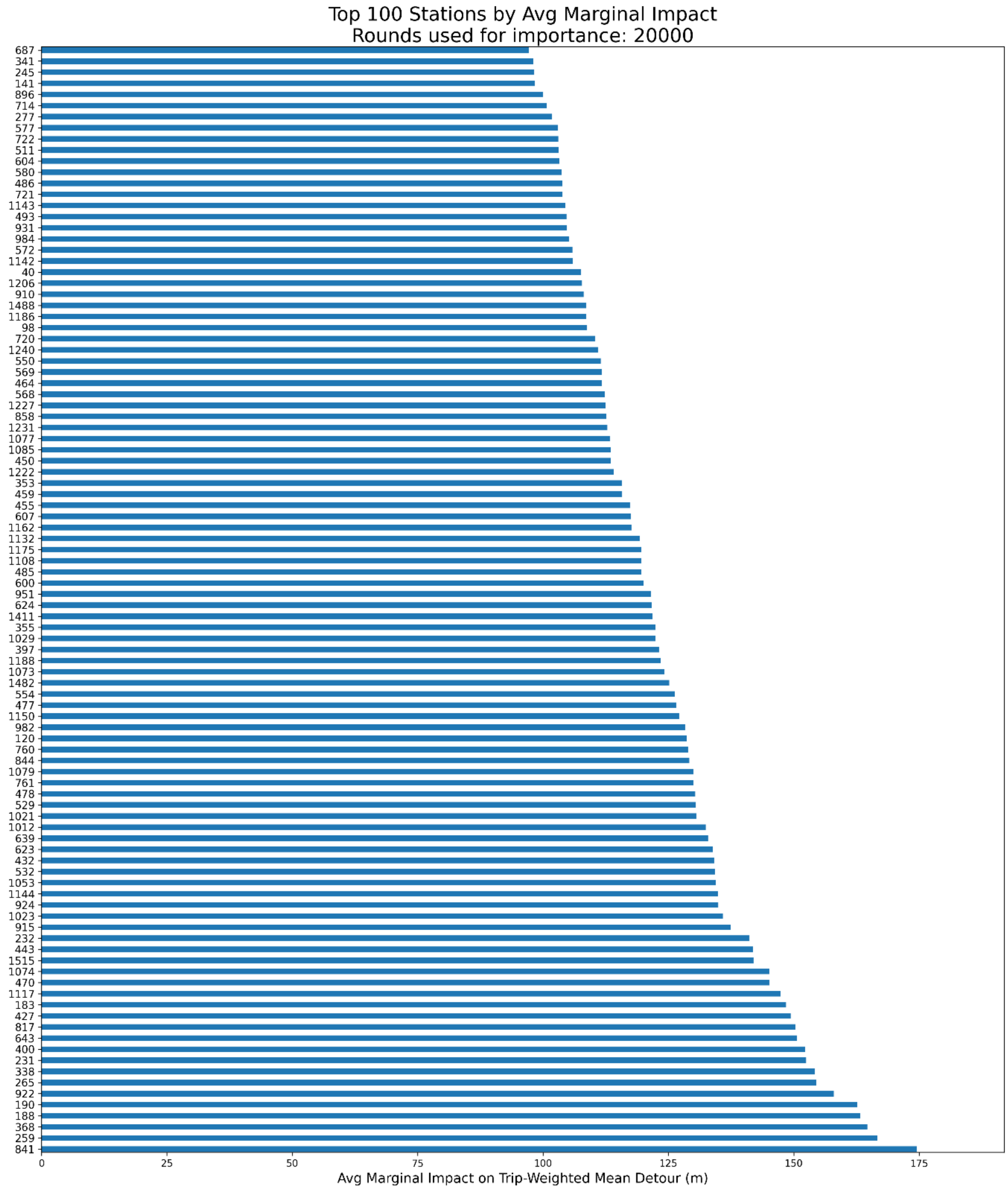

Figure 23 Top-100 Gas Stations Ranked by Average Marginal Impact on Trip-Weighted Mean Detour

Sharp peaks in marginal detour (slope) and corresponding curvature spikes indicate that the loss of these high-impact stations accelerates the deterioration of refueling accessibility far more than the loss of typical stations. From a planning standpoint, preserving, retrofitting, or converting this limited set of structurally influential stations into hybrid or dual-fuel facilities can meaningfully delay the emergence of refueling deserts and maintain system stability deeper into the transition period.

The spatial distribution of these high-impact stations further supports this interpretation. Figure 24 maps the Top-100 stations and shows that they cluster along Calgary's primary mobility spine and major corridors, most notably Macleod Trail, the Trans-Canada Highway / 16 Ave NW, Sarcee Trail, and 17 Ave SE, with additional concentration near the central area. In network terms, these locations function as throughput backbones and "bridge links" between large OD regions; stations situated on or near them become leverage points, so their loss produces network-wide detour inflation that cannot be compensated by peripheral redundancy.

Figure 24 Spatial heatmap of Top-100 high-impact stations, highlighting corridor-aligned clusters

The complete ranked list of all stations (**n = 311**), along with their average marginal impacts, is provided in Appendix C (Table C.1). This full table supports the interpretation above by identifying precisely which stations anchor the resilience of Calgary's refueling network during ZEV-driven contraction, and therefore which sites are the highest-value candidates for protection, retrofit, or managed conversion.

5.4.3 Timing Matters More Than Scale

The analysis shows that **when** intervention occurs is more consequential than **how large** the intervention is. Before 2035, the refueling network operates in a redundancy-dominated regime where detour levels are uniformly low and closure order has minimal effect; any preservation effort during this stage produces negligible system-wide benefit. After 2045, the network has already entered the fragility-driven regime, where even substantial interventions cannot reverse the nonlinear escalation of detour burdens.

The meaningful planning window lies between 2035 and 2045, where the system transitions from stable to sensitive. During this period, small, targeted actions, such as preserving the highest-impact stations, can prevent the rapid onset of network collapse and maintain acceptable refueling accessibility with comparatively limited investment.

5.5 Broader Implications for Urban Fueling Transitions

Although this analysis is rooted in Calgary's urban form and station distribution, several findings extend well beyond the local context and speak to how cities should manage gasoline-network decline during large-scale electrification:

Transitional infrastructure planning must account for network geometry, not just infrastructure quantity. The results show that detour escalation is driven by *where* stations are lost, not simply *how many*. Cities with dispersed travel patterns or corridor-dependent movement will experience nonlinear degradation once spatial redundancy disappears. This means policymakers cannot rely on station counts alone; they must protect geometrically strategic locations.

Behavioral thresholds provide clearer guidance than relative performance metrics because they translate outcomes into operational meaning. In this study, the acceptable detour $\Delta D^* = 1.6$ km defines a hard boundary for functional adequacy, while the curve-based markers ASC, ConSC, and CSC locate when the refueling detour begins accelerating (ASC ≈ 2034), reaches noticeable inconvenience (ConSC > 0.6 km at ≈ 2039), and crosses into systematic inadequacy (CSC where mean exceeds ΔD^* at ≈ 2046). By contrast, relative metrics (e.g., percent change from baseline) can indicate deterioration but cannot specify when user burden becomes unacceptable or when small additional closures trigger disproportionate impacts. Behavioral thresholds and sensitivity markers therefore provide more actionable decision points for timing interventions and prioritizing mitigation.

Dual-fuel or hybrid facilities are likely necessary during extended transition periods. Because the gasoline network becomes configuration-sensitive long before it becomes sparse, maintaining some stations with both gasoline and charging capabilities can stabilize accessibility for remaining ICE users while supporting EV adoption. These hybrid facilities serve as intentional buffers against premature fuel-desert formation.

Gasoline infrastructure should be treated as critical urban service infrastructure, not merely a private commodity. Left entirely to market forces, random closures risk creating accessibility failures that disproportionately affect specific neighborhoods, commute corridors, and vulnerable users. The results demonstrate that refueling access functions as a public-interest service, requiring oversight, coordination, and occasionally targeted preservation.

These insights are directly relevant for jurisdictions pursuing aggressive ZEV adoption without coordinated plans for the residual ICE fleet. Even in high EV penetration futures, legacy refueling infrastructure must be managed deliberately to avoid accessibility gaps, disproportionate burdens, and unintended mobility inequities.

5.6 Limitations and Directions for Future Research

This study intentionally simplifies several components to isolate the structural behavior of the refueling network and to support clear interpretation of detour dynamics. In particular, the framework adopts progressive random station-removal sequences, treats closures as independent events with homogeneous closure likelihood across the study area, assumes static travel demand, represents drivers as selecting the minimum-detour station, and evaluates network performance under average traffic conditions. In addition, gasoline demand decline and station-closure levels are linked through simplified proportional relationships, while charging infrastructure growth is not explicitly modeled. These assumptions are appropriate for a first-order, system-level assessment of refueling accessibility risk and transition thresholds, but they abstract from strategic supplier behavior, spatial autocorrelation in station exits, regional heterogeneity in demand and EV uptake, behavioral adaptation by drivers, and time-varying traffic conditions. Accordingly, the findings should be interpreted as baseline scenario-based planning evidence rather than parcel-level forecasts, and future research should focus on sensitivity analysis and model extensions that investigate these assumptions.

5.7 Future research areas

Future research could extend the present framework through targeted sensitivity analysis and model refinement in the following areas:

Strategic and spatially dependent station closures: Replace purely random removals with closure models that incorporate strategic supplier behavior, coordinated withdrawals, targeted preservation of high-impact stations, and spatial autocorrelation or clustering in station exits. Future models could represent closure decisions using economic or operational decision rules (e.g., throughput, lease conditions, land value, proximity to competing stations, or corridor importance), while also allowing nearby stations to share correlated closure risk. This would better reflect real-world market contraction and would help determine whether strategic behavior accelerates, delays, or spatially concentrates network fragility.

Heterogeneity-aware closure likelihood and demand patterns: Condition station vulnerability on neighborhood demand, demographics, income, land use, regional EV uptake, station type, and local traffic intensity to better represent uneven transition dynamics across the urban area. Rather than assigning equal closure likelihood at a given contraction level, future work could estimate differentiated closure probabilities using subarea-specific indicators and station attributes. This would improve realism and allow assessment of whether certain communities or corridors experience disproportionately higher refueling burdens during the transition.

Sensitivity to transition and closure assumptions: Evaluate how results change under alternative ZEV adoption trajectories (slower or more accelerated pathways) and under nonlinear mappings between ZEV uptake, gasoline demand reduction, and station closures. A structured sensitivity-analysis framework could test the robustness of key outputs, including milestone detour values and threshold locations (e.g., ConSC, ASC, CSC), to changes in the core assumptions introduced in this thesis. This would clarify which assumptions most strongly influence the conclusions and would improve confidence in the framework's planning relevance.

Dynamic travel demand and behavioral adaptation: Incorporate demand growth/decline, land-use change, temporal variation, trip chaining, route adaptation, and non-distance-based station choice behavior (e.g., brand loyalty, price sensitivity, and queue avoidance). Future extensions could combine network accessibility modeling with behavioral choice models or activity-based demand frameworks so that drivers respond adaptively to declining station availability rather than remaining fixed in their refueling behavior. This would allow estimation of both structural burden and behavioral mitigation effects, producing a more realistic representation of transition impacts.

Dynamic traffic conditions and time-based burden metrics: Extend the analysis beyond average-condition distances by incorporating congestion, peak-period variability, incidents, and dynamic traffic assignment to estimate refueling burden in travel-time terms. This would enable evaluation of whether the same detour distance produces substantially different burdens under congested versus uncongested conditions, especially near high-demand corridors or surviving stations. Time-based metrics could also support more policy-relevant interpretation in terms of operational delay, reliability, and peak-period vulnerability.

Co-evolution of gasoline and charging infrastructure: Explicitly model charging-network expansion and its interaction with gasoline demand decline to examine transitional dual-fuel accessibility, bottlenecks, and cross-fuel infrastructure dependencies. Instead of treating charging growth as an external driver only, future studies could simulate the parallel evolution of gasoline and charging networks, including spatial competition, substitution effects, and timing mismatches between declining gasoline capacity and expanding charging capacity. This would be particularly valuable for identifying transition periods in which both systems are simultaneously constrained.

Multi-scale and province-wide applications: Link within-city results to between-city travel corridors and provincial networks to identify stations that are locally important and regionally critical for long-distance mobility continuity. Future work could integrate urban OD-based refueling burdens with intercity corridor accessibility (e.g., major highways and regional travel routes). This would support province-scale planning for strategic preservation, conversion, or phased transition of stations that serve dual local and corridor functions.

Empirical calibration and stakeholder validation: Use station inventory time series, observed closures, operator interviews, and driver surveys to calibrate closure mechanisms, validate behavioral assumptions, and improve model realism. Longitudinal station data could help estimate closure probabilities and spatial clustering patterns, while stakeholder engagement could reveal operational constraints and decision drivers not visible in network geometry alone. Such calibration and validation would strengthen the evidence base for applying the framework in planning and policy contexts.

Comparative application across urban forms: Apply the methodology to cities and provinces with different spatial morphologies and travel structures to test transferability and refine the generalizability of the framework. Comparing auto-oriented, dispersed urban forms with denser, transit-oriented regions would help determine how redundancy, configuration sensitivity, and nonlinear detour escalation vary by spatial context. Cross-city comparison would also support development of more general planning guidance on where and when fuel-network contraction is most likely to create accessibility risks.

5.8 Chapter Summary

This chapter demonstrated that:

- **Gasoline refueling networks can become operationally inadequate before physical disappearance**, as accessibility burdens rise substantially while a nontrivial number of stations still remain in service.
- **Network degradation is driven by the loss of spatial redundancy and configuration resilience, not station count alone**, meaning that where closures occur can matter as much as how many closures occur.
- **Refueling burden escalation is nonlinear**, with a transition window in which detour impacts increase disproportionately as the network loses redundancy and alternative refueling options become less available.
- **Targeted planning and managed transition strategies can meaningfully delay system inadequacy**, particularly when high-impact stations and corridor-supporting locations are identified and considered in transition planning.

Overall, the chapter reframed gasoline station decline as a **network accessibility and infrastructure-planning problem**, rather than only a retail-market contraction issue. The findings provide a quantitative basis for interpreting transition risk, identifying emerging vulnerability regimes, and supporting more proactive planning during the ZEV transition. In this sense, the study's results contribute not only to understanding refueling detour burdens in Calgary, but also to the broader discussion of how urban fuel systems can be managed during long-term transportation decarbonization.

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APPENDICES

APPENDIX A:

Table A-1 Mean Detour, Slope, and Curvature Metrics Table

Stations Removed (k)	Stations Remaining	Milestone Year	Weighted ΔD (km)	Unweighted ΔD (km)	Slope (ΔD/removed station)	Curvature (ΔD/removed station²)
0	311	2025	0.19375	0.09942		
1	310		0.19456	0.09973	0.81025	
2	309		0.19537	0.10004	0.80985	-0.0004
3	308		0.19617	0.10035	0.79961	-0.01024
4	307		0.19699	0.10067	0.8167	0.01709
5	306		0.19781	0.10099	0.81728	0.00058
6	305		0.19862	0.10131	0.81635	-0.00094
7	304		0.19946	0.10163	0.83522	0.01888
8	303		0.2003	0.10196	0.83804	0.00282
9	302		0.20113	0.10228	0.83096	-0.00708
10	301		0.20197	0.10262	0.8405	0.00954
11	300		0.20283	0.10295	0.86109	0.02059
12	299		0.20368	0.10328	0.85396	-0.00714
13	298		0.20453	0.10362	0.85339	-0.00057
14	297		0.20541	0.10397	0.87349	0.0201
15	296		0.2063	0.10432	0.89018	0.01669
16	295		0.2072	0.10467	0.89686	0.00668
17	294		0.20807	0.10502	0.87109	-0.02576
18	293		0.20897	0.10537	0.9044	0.0333
19	292		0.20988	0.10572	0.90878	0.00438
20	291		0.21079	0.10609	0.90684	-0.00194
21	290		0.21171	0.10644	0.92222	0.01538
22	289		0.21262	0.10681	0.91301	-0.00921
23	288		0.21354	0.10717	0.92	0.00699
24	287		0.21447	0.10754	0.925	0.00501
25	286		0.21541	0.10792	0.94555	0.02055
26	285		0.21633	0.10828	0.91496	-0.03059
27	284		0.21728	0.10866	0.95579	0.04083
28	283		0.21823	0.10904	0.94418	-0.01161
29	282		0.21918	0.10942	0.94774	0.00356
30	281		0.22018	0.1098	1.00031	0.05257
31	280		0.22117	0.1102	0.98984	-0.01048
32	279		0.22215	0.11059	0.98941	-0.00043
33	278		0.22312	0.11097	0.96996	-0.01945
34	277		0.22411	0.11136	0.98711	0.01715

35	276		0.22511	0.11175	0.99641	0.0093
36	275		0.22612	0.11215	1.01323	0.01682
37	274		0.22713	0.11255	1.01167	-0.00156
38	273		0.22815	0.11295	1.01595	0.00428
39	272		0.22919	0.11336	1.03809	0.02214
40	271		0.23022	0.11377	1.03168	-0.00641
41	270		0.23127	0.11419	1.04831	0.01663
42	269		0.23233	0.11462	1.06473	0.01642
43	268		0.23338	0.11504	1.04591	-0.01882
44	267		0.23446	0.11547	1.08607	0.04016
45	266		0.23555	0.1159	1.09015	0.00408
46	265		0.23663	0.11634	1.07954	-0.01061
47	264		0.23772	0.11678	1.08537	0.00583
48	263		0.23884	0.11722	1.12537	0.03999
49	262		0.23996	0.11766	1.11531	-0.01006
50	261		0.24108	0.1181	1.12142	0.00611
51	260		0.24222	0.11855	1.1365	0.01508
52	259		0.24334	0.119	1.12334	-0.01316
53	258		0.24447	0.11945	1.12727	0.00393
54	257		0.24561	0.11991	1.13809	0.01082
55	256		0.24678	0.12038	1.17636	0.03827
56	255		0.24797	0.12085	1.18777	0.01141
57	254		0.24913	0.12132	1.16223	-0.02554
58	253		0.25033	0.12179	1.19548	0.03324
59	252		0.25152	0.12228	1.19191	-0.00356
60	251		0.2527	0.12277	1.18291	-0.009
61	250		0.25391	0.12326	1.20476	0.02185
62	249		0.25513	0.12375	1.22499	0.02024
63	248		0.25637	0.12425	1.23516	0.01016
64	247		0.25761	0.12474	1.24261	0.00745
65	246		0.25889	0.12525	1.27962	0.03701
66	245		0.26019	0.12578	1.30141	0.02179
67	244		0.26145	0.12629	1.26249	-0.03892
68	243		0.26274	0.12682	1.28189	0.0194
69	242		0.26403	0.12735	1.29828	0.01639
70	241		0.26534	0.12787	1.31053	0.01225
71	240		0.26667	0.1284	1.3257	0.01517
72	239		0.268	0.12894	1.33306	0.00736
73	238		0.26938	0.12949	1.37782	0.04476
74	237		0.27072	0.13004	1.3366	-0.04122
75	236	2030	0.27207	0.13059	1.34906	0.01246
76	235		0.27342	0.13115	1.35651	0.00745
77	234		0.2748	0.13171	1.37752	0.02101

78	233		0.27619	0.13227	1.38775	0.01022
79	232		0.27758	0.13285	1.39627	0.00852
80	231		0.27904	0.13343	1.45525	0.05898
81	230		0.28047	0.13401	1.42577	-0.02947
82	229		0.28191	0.13459	1.44801	0.02223
83	228		0.28337	0.13518	1.45587	0.00787
84	227		0.28486	0.13577	1.49226	0.03639
85	226		0.28635	0.13638	1.4886	-0.00367
86	225		0.28786	0.13701	1.51351	0.02491
87	224		0.28939	0.13762	1.52239	0.00888
88	223		0.29093	0.13826	1.54629	0.0239
89	222		0.2925	0.13889	1.5642	0.01791
90	221		0.29406	0.13953	1.564	-0.00021
91	220		0.29565	0.14018	1.58808	0.02408
92	219		0.29724	0.14082	1.59159	0.00352
93	218		0.29885	0.14149	1.60566	0.01407
94	217		0.30047	0.14215	1.61988	0.01422
95	216		0.30211	0.14284	1.64309	0.02322
96	215		0.30376	0.1435	1.65576	0.01267
97	214		0.30545	0.14419	1.68967	0.03392
98	213		0.30715	0.14487	1.69227	0.00259
99	212		0.30885	0.14559	1.70445	0.01219
100	211		0.31057	0.1463	1.72079	0.01633
101	210		0.31228	0.147	1.7035	-0.01729
102	209		0.31403	0.14772	1.75163	0.04813
103	208		0.31575	0.14843	1.72642	-0.02521
104	207		0.31756	0.14917	1.80444	0.07802
105	206		0.31931	0.14988	1.7522	-0.05224
106	205		0.32108	0.15061	1.77237	0.02018
107	204		0.32286	0.15136	1.78003	0.00766
108	203		0.32468	0.15214	1.81574	0.0357
109	202		0.32651	0.1529	1.82983	0.0141
110	201		0.32837	0.15367	1.86238	0.03254
111	200		0.33026	0.15445	1.88711	0.02474
112	199		0.33215	0.15522	1.88771	0.0006
113	198		0.33407	0.156	1.92133	0.03362
114	197		0.33604	0.15682	1.9756	0.05427
115	196		0.33801	0.15763	1.96984	-0.00575
116	195		0.33996	0.15843	1.94755	-0.02229
117	194		0.34196	0.15926	2.00382	0.05627
118	193		0.34401	0.16011	2.04977	0.04596
119	192		0.34605	0.16095	2.03514	-0.01463
120	191		0.34811	0.16181	2.06068	0.02554

121	190		0.35016	0.16267	2.04971	-0.01097
122	189		0.35219	0.1635	2.02674	-0.02298
123	188		0.35434	0.1644	2.15533	0.1286
124	187		0.35652	0.16529	2.18195	0.02661
125	186		0.35869	0.1662	2.16794	-0.01401
126	185		0.36087	0.16712	2.18177	0.01383
127	184		0.36309	0.16804	2.21738	0.03561
128	183		0.36534	0.16897	2.24563	0.02825
129	182		0.36761	0.16992	2.27138	0.02575
130	181		0.36992	0.17087	2.31245	0.04107
131	180		0.3722	0.17183	2.28274	-0.02971
132	179		0.37458	0.17279	2.37966	0.09692
133	178		0.37693	0.17376	2.35155	-0.0281
134	177		0.37935	0.17475	2.4195	0.06795
135	176		0.38174	0.17575	2.38487	-0.03463
136	175		0.38415	0.17678	2.41596	0.03108
137	174		0.38664	0.17778	2.4879	0.07194
138	173		0.38917	0.17883	2.52712	0.03922
139	172		0.39173	0.17989	2.56115	0.03403
140	171		0.39431	0.18097	2.57629	0.01514
141	170		0.39694	0.18204	2.6384	0.06211
142	169		0.39953	0.18313	2.58726	-0.05114
143	168		0.40216	0.18423	2.62991	0.04265
144	167	2035	0.40478	0.18534	2.61804	-0.01186
145	166		0.40748	0.18646	2.70212	0.08407
146	165		0.41018	0.1876	2.69932	-0.0028
147	164		0.41293	0.18874	2.74694	0.04762
148	163		0.41573	0.1899	2.80449	0.05755
149	162		0.4186	0.19111	2.86907	0.06458
150	161		0.42141	0.1923	2.81072	-0.05835
151	160		0.42426	0.19349	2.85077	0.04005
152	159		0.42722	0.19471	2.95424	0.10347
153	158		0.43017	0.19594	2.95416	-9.00E-05
154	157		0.43325	0.19725	3.07545	0.1213
155	156		0.43632	0.19855	3.07563	0.00018
156	155		0.43943	0.19987	3.10254	0.02691
157	154		0.44258	0.20118	3.1521	0.04956
158	153		0.44576	0.20252	3.18256	0.03046
159	152		0.44907	0.20391	3.3105	0.12794
160	151		0.45236	0.20528	3.28818	-0.02232
161	150		0.45573	0.2067	3.37613	0.08795
162	149		0.4591	0.20812	3.36385	-0.01228
163	148		0.46247	0.20956	3.3693	0.00545

164	147		0.46595	0.21101	3.48175	0.11244
165	146		0.46956	0.21249	3.61341	0.13167
166	145		0.47314	0.214	3.57407	-0.03934
167	144		0.47679	0.21555	3.64923	0.07516
168	143		0.48044	0.21711	3.65159	0.00235
169	142		0.48403	0.21866	3.59365	-0.05794
170	141		0.48779	0.22022	3.76275	0.1691
171	140		0.49159	0.22183	3.79771	0.03496
172	139		0.49547	0.22347	3.87338	0.07567
173	138		0.49936	0.22514	3.89391	0.02053
174	137		0.50332	0.22685	3.95793	0.06402
175	136		0.50733	0.22853	4.01551	0.05758
176	135		0.51128	0.23024	3.94779	-0.06771
177	134		0.5155	0.23204	4.21733	0.26953
178	133		0.51972	0.2338	4.21768	0.00036
179	132		0.52391	0.23559	4.19885	-0.01884
180	131		0.52828	0.2374	4.36401	0.16516
181	130		0.53269	0.23928	4.40753	0.04351
182	129		0.53702	0.24112	4.3323	-0.07522
183	128		0.54144	0.24303	4.4201	0.0878
184	127		0.54599	0.24497	4.55046	0.13036
185	126		0.55055	0.24689	4.56202	0.01156
186	125		0.55523	0.24891	4.67581	0.11379
187	124		0.56017	0.25102	4.94158	0.26578
188	123		0.56516	0.2531	4.98682	0.04524
189	122		0.56996	0.25516	4.80837	-0.17846
190	121		0.57499	0.25731	5.02449	0.21613
191	120		0.58012	0.25942	5.12773	0.10324
192	119		0.58529	0.26168	5.16999	0.04226
193	118		0.59049	0.264	5.20581	0.03582
194	117		0.5958	0.26627	5.30541	0.0996
195	116		0.60125	0.26867	5.45341	0.148
196	115		0.6067	0.27101	5.44941	-0.00399
197	114		0.61236	0.27342	5.66423	0.21482
198	113		0.61817	0.2759	5.80734	0.14311
199	112		0.62405	0.27838	5.87606	0.06872
200	111		0.62982	0.28082	5.77176	-0.10431
201	110		0.63581	0.28347	5.9945	0.22274
202	109		0.64204	0.28616	6.22147	0.22697
203	108		0.6481	0.28879	6.06692	-0.15455
204	107		0.65449	0.29158	6.39123	0.32431
205	106		0.6609	0.29437	6.40869	0.01746
206	105	2040	0.66753	0.29721	6.62386	0.21517

207	104		0.67418	0.30012	6.65623	0.03237
208	103		0.68101	0.30308	6.82634	0.17011
209	102		0.68802	0.3061	7.01028	0.18394
210	101		0.69523	0.3092	7.21592	0.20564
211	100		0.70243	0.31233	7.19965	-0.01627
212	99		0.70965	0.31546	7.21312	0.01347
213	98		0.71709	0.3187	7.44456	0.23144
214	97		0.72463	0.32202	7.53886	0.09429
215	96		0.73233	0.32535	7.69943	0.16057
216	95		0.74009	0.32878	7.7647	0.06527
217	94		0.74819	0.33231	8.09413	0.32943
218	93		0.75658	0.33599	8.39454	0.30041
219	92		0.76496	0.33964	8.38035	-0.01419
220	91		0.77341	0.3433	8.44884	0.06849
221	90		0.78223	0.34718	8.81261	0.36377
222	89		0.79119	0.35112	8.96442	0.15181
223	88		0.80036	0.35513	9.16857	0.20415
224	87		0.80943	0.35918	9.07379	-0.09477
225	86		0.81902	0.36341	9.58645	0.51266
226	85		0.82868	0.36767	9.6609	0.07445
227	84		0.83879	0.37211	10.11211	0.45121
228	83		0.84923	0.37666	10.436	0.32389
229	82		0.85986	0.38126	10.6346	0.1986
230	81		0.87059	0.38596	10.7289	0.09429
231	80		0.88161	0.3908	11.01786	0.28896
232	79		0.89275	0.39568	11.13802	0.12016
233	78		0.90429	0.40075	11.54488	0.40686
234	77		0.91639	0.40609	12.09742	0.55254
235	76		0.92832	0.41133	11.92671	-0.17071
236	75		0.94116	0.41683	12.84444	0.91773
237	74		0.95418	0.42249	13.01903	0.17458
238	73		0.96748	0.42838	13.30411	0.28509
239	72		0.98027	0.43411	12.7846	-0.51951
240	71		0.9939	0.4401	13.6286	0.844
241	70		1.00813	0.44637	14.22864	0.60004
242	69		1.02253	0.45283	14.40859	0.17995
243	68		1.03762	0.45949	15.08641	0.67782
244	67		1.05345	0.46651	15.82539	0.73898
245	66		1.06932	0.4738	15.87093	0.04554
246	65		1.08546	0.48101	16.1469	0.27597
247	64		1.10207	0.48832	16.60204	0.45514
248	63		1.11926	0.49609	17.19117	0.58913
249	62		1.13688	0.50389	17.61901	0.42784

250	61		1.15487	0.5119	17.99595	0.37694
251	60		1.1739	0.52041	19.02771	1.03176
252	59		1.19373	0.52932	19.83535	0.80764
253	58		1.21369	0.53837	19.95111	0.11575
254	57		1.23425	0.54772	20.56658	0.61548
255	56		1.25617	0.55772	21.91877	1.35219
256	55		1.27807	0.56773	21.90089	-0.01788
257	54		1.30091	0.57813	22.83895	0.93806
258	53		1.32451	0.58895	23.60177	0.76282
259	52	2045	1.34933	0.60026	24.82104	1.21927
260	51		1.37517	0.61224	25.83933	1.01829
261	50		1.40213	0.62448	26.95251	1.11318
262	49		1.4296	0.63717	27.47178	0.51928
263	48		1.45834	0.65037	28.74446	1.27268
264	47		1.48825	0.66417	29.90866	1.1642
265	46		1.51984	0.67869	31.59261	1.68395
266	45		1.55212	0.69347	32.27973	0.68712
267	44		1.58634	0.70911	34.21545	1.93572
268	43		1.62157	0.72532	35.23564	1.02019
269	42		1.65814	0.74223	36.56101	1.32537
270	41		1.69613	0.75976	37.99725	1.43623
271	40		1.73585	0.7785	39.72208	1.72484
272	39		1.77912	0.7989	43.26391	3.54183
273	38		1.82297	0.81921	43.85269	0.58877
274	37		1.86852	0.8408	45.54534	1.69265
275	36		1.91667	0.86374	48.14875	2.60341
276	35		1.96618	0.8876	49.51179	1.36304
277	34		2.01917	0.91299	52.99187	3.48008
278	33		2.07676	0.941	57.58929	4.59743
279	32		2.13838	0.97034	61.62357	4.03428
280	31		2.20121	1.00091	62.82997	1.2064
281	30		2.26881	1.03406	67.60097	4.77099
282	29		2.33897	1.06824	70.15848	2.55752
283	28		2.41361	1.10513	74.63431	4.47583
284	27		2.4963	1.14612	82.69858	8.06427
285	26		2.58304	1.18932	86.73143	4.03285
286	25		2.67633	1.23648	93.29295	6.56152
287	24		2.77312	1.2855	96.78674	3.49379
288	23		2.88055	1.33996	107.4357	10.64897
289	22		2.99714	1.39981	116.59241	9.1567
290	21		3.11635	1.46134	119.20547	2.61307
291	20		3.25025	1.53054	133.89635	14.69088
292	19		3.39566	1.60823	145.41745	11.5211

293	18		3.55617	1.69394	160.50386	15.08641
294	17		3.7303	1.78892	174.13354	13.62967
295	16		3.91938	1.89186	189.07857	14.94503
296	15	2050	4.13792	2.01304	218.53948	29.46091
297	14		4.37714	2.14826	239.21776	20.67828
298	13		4.65069	2.30382	273.55623	34.33847
299	12		4.94987	2.47893	299.18289	25.62666
300	11		5.2939	2.68351	344.0299	44.84701
301	10		5.69961	2.92924	405.70259	61.67269
302	9		6.1767	3.22246	477.09513	71.39254
303	8		6.75194	3.5867	575.23346	98.13833
304	7		7.43571	4.03023	683.77113	108.53767
305	6		8.32076	4.62124	885.04982	201.27869
306	5		9.4431	5.39495	1122.33829	237.28848
307	4		10.97581	6.49748	1532.7158	410.3775
308	3		13.23951	8.2152	2263.70335	730.98755
309	2		17.00114	11.24177	3761.62624	1497.9229
310	1		25.61634	18.75523	8615.19814	4853.57189

APPENDIX B:

Table B.1. Stability Metrics Across Random-Subset Monte Carlo Increments (1,000–20,000 Runs)

Sample Rep	Sample Seed	R Runs	Milestone Year	Stations Remaining	Mean Detour (km)	ΔD vs Prev (km)	ΔD vs Prev (%)	Top-100 Overlap vs Prev	Top-100 Jaccard vs Prev
0	20260130	1000	2025	311	0.19377				
0	20260130	1000	2030	236	0.271819				
0	20260130	1000	2035	167	0.405212				
0	20260130	1000	2040	105	0.669456				
0	20260130	1000	2045	52	1.358314				
0	20260130	1000	2050	15	4.159027				
0	20260130	2000	2025	311	0.19377	0	0	69	0.527
0	20260130	2000	2030	236	0.271823	5.00E-06	0.002	69	0.527
0	20260130	2000	2035	167	0.403753	-0.00146	-0.36	69	0.527
0	20260130	2000	2040	105	0.664791	-0.00467	-0.697	69	0.527
0	20260130	2000	2045	52	1.349512	-0.0088	-0.648	69	0.527
0	20260130	2000	2050	15	4.119492	-0.03954	-0.951	69	0.527
0	20260130	3000	2025	311	0.19377	0	0	75	0.6
0	20260130	3000	2030	236	0.272389	0.000565	0.208	75	0.6
0	20260130	3000	2035	167	0.404902	0.001149	0.285	75	0.6

0	20260130	3000	2040	105	0.668922	0.004131	0.621	75	0.6
0	20260130	3000	2045	52	1.353106	0.003594	0.266	75	0.6
0	20260130	3000	2050	15	4.132554	0.013062	0.317	75	0.6
0	20260130	4000	2025	311	0.19377	0	0	78	0.639
0	20260130	4000	2030	236	0.272364	-2.50E-05	-0.009	78	0.639
0	20260130	4000	2035	167	0.404769	-0.00013	-0.033	78	0.639
0	20260130	4000	2040	105	0.666951	-0.00197	-0.295	78	0.639
0	20260130	4000	2045	52	1.348346	-0.00476	-0.352	78	0.639
0	20260130	4000	2050	15	4.118727	-0.01383	-0.335	78	0.639
0	20260130	5000	2025	311	0.19377	0	0	84	0.724
0	20260130	5000	2030	236	0.272158	-0.00021	-0.076	84	0.724
0	20260130	5000	2035	167	0.404707	-6.20E-05	-0.015	84	0.724
0	20260130	5000	2040	105	0.66617	-0.00078	-0.117	84	0.724
0	20260130	5000	2045	52	1.347391	-0.00096	-0.071	84	0.724
0	20260130	5000	2050	15	4.133199	0.014472	0.351	84	0.724
0	20260130	6000	2025	311	0.19377	0	0	85	0.739
0	20260130	6000	2030	236	0.272275	0.000117	0.043	85	0.739
0	20260130	6000	2035	167	0.40473	2.30E-05	0.006	85	0.739
0	20260130	6000	2040	105	0.667667	0.001497	0.225	85	0.739
0	20260130	6000	2045	52	1.348802	0.00141	0.105	85	0.739
0	20260130	6000	2050	15	4.123837	-0.00936	-0.226	85	0.739
0	20260130	7000	2025	311	0.19377	0	0	89	0.802
0	20260130	7000	2030	236	0.272289	1.40E-05	0.005	89	0.802
0	20260130	7000	2035	167	0.404685	-4.50E-05	-0.011	89	0.802
0	20260130	7000	2040	105	0.668038	0.000371	0.056	89	0.802
0	20260130	7000	2045	52	1.347373	-0.00143	-0.106	89	0.802
0	20260130	7000	2050	15	4.132942	0.009105	0.221	89	0.802
0	20260130	8000	2025	311	0.19377	0	0	90	0.818
0	20260130	8000	2030	236	0.272217	-7.20E-05	-0.026	90	0.818
0	20260130	8000	2035	167	0.405099	0.000414	0.102	90	0.818
0	20260130	8000	2040	105	0.667265	-0.00077	-0.116	90	0.818
0	20260130	8000	2045	52	1.34892	0.001547	0.115	90	0.818
0	20260130	8000	2050	15	4.133775	0.000833	0.02	90	0.818
0	20260130	9000	2025	311	0.19377	0	0	89	0.802
0	20260130	9000	2030	236	0.272136	-8.10E-05	-0.03	89	0.802
0	20260130	9000	2035	167	0.404854	-0.00025	-0.06	89	0.802
0	20260130	9000	2040	105	0.668097	0.000832	0.125	89	0.802
0	20260130	9000	2045	52	1.350167	0.001248	0.092	89	0.802
0	20260130	9000	2050	15	4.132244	-0.00153	-0.037	89	0.802
0	20260130	10000	2025	311	0.19377	0	0	89	0.802
0	20260130	10000	2030	236	0.272445	0.000309	0.114	89	0.802
0	20260130	10000	2035	167	0.405004	0.00015	0.037	89	0.802
0	20260130	10000	2040	105	0.667987	-0.00011	-0.016	89	0.802

0	20260130	10000	2045	52	1.351065	0.000898	0.066	89	0.802
0	20260130	10000	2050	15	4.127158	-0.00509	-0.123	89	0.802
0	20260130	11000	2025	311	0.19377	0	0	91	0.835
0	20260130	11000	2030	236	0.272267	-0.00018	-0.065	91	0.835
0	20260130	11000	2035	167	0.404847	-0.00016	-0.039	91	0.835
0	20260130	11000	2040	105	0.667135	-0.00085	-0.128	91	0.835
0	20260130	11000	2045	52	1.350858	-0.00021	-0.015	91	0.835
0	20260130	11000	2050	15	4.144919	0.017761	0.43	91	0.835
0	20260130	12000	2025	311	0.19377	0	0	90	0.818
0	20260130	12000	2030	236	0.272188	-7.80E-05	-0.029	90	0.818
0	20260130	12000	2035	167	0.404855	8.00E-06	0.002	90	0.818
0	20260130	12000	2040	105	0.66771	0.000575	0.086	90	0.818
0	20260130	12000	2045	52	1.351471	0.000613	0.045	90	0.818
0	20260130	12000	2050	15	4.140745	-0.00417	-0.101	90	0.818
0	20260130	13000	2025	311	0.19377	0	0	91	0.835
0	20260130	13000	2030	236	0.272149	-3.90E-05	-0.014	91	0.835
0	20260130	13000	2035	167	0.404742	-0.00011	-0.028	91	0.835
0	20260130	13000	2040	105	0.667248	-0.00046	-0.069	91	0.835
0	20260130	13000	2045	52	1.348834	-0.00264	-0.195	91	0.835
0	20260130	13000	2050	15	4.131862	-0.00888	-0.215	91	0.835
0	20260130	14000	2025	311	0.19377	0	0	93	0.869
0	20260130	14000	2030	236	0.272214	6.50E-05	0.024	93	0.869
0	20260130	14000	2035	167	0.40482	7.90E-05	0.019	93	0.869
0	20260130	14000	2040	105	0.667659	0.00041	0.062	93	0.869
0	20260130	14000	2045	52	1.350866	0.002032	0.151	93	0.869
0	20260130	14000	2050	15	4.139214	0.007352	0.178	93	0.869
0	20260130	15000	2025	311	0.19377	0	0	95	0.905
0	20260130	15000	2030	236	0.272176	-3.80E-05	-0.014	95	0.905
0	20260130	15000	2035	167	0.404685	-0.00014	-0.033	95	0.905
0	20260130	15000	2040	105	0.667033	-0.00063	-0.094	95	0.905
0	20260130	15000	2045	52	1.348641	-0.00223	-0.165	95	0.905
0	20260130	15000	2050	15	4.134603	-0.00461	-0.111	95	0.905
0	20260130	16000	2025	311	0.19377	0	0	97	0.942
0	20260130	16000	2030	236	0.2722	2.40E-05	0.009	97	0.942
0	20260130	16000	2035	167	0.404889	0.000204	0.05	97	0.942
0	20260130	16000	2040	105	0.667299	0.000266	0.04	97	0.942
0	20260130	16000	2045	52	1.348868	0.000227	0.017	97	0.942
0	20260130	16000	2050	15	4.13284	-0.00176	-0.043	97	0.942
0	20260130	17000	2025	311	0.19377	0	0	97	0.942
0	20260130	17000	2030	236	0.272234	3.40E-05	0.013	97	0.942
0	20260130	17000	2035	167	0.405001	0.000112	0.028	97	0.942
0	20260130	17000	2040	105	0.667824	0.000525	0.079	97	0.942
0	20260130	17000	2045	52	1.351917	0.00305	0.226	97	0.942

0	20260130	17000	2050	15	4.137185	0.004345	0.105	97	0.942
0	20260130	18000	2025	311	0.19377	0	0	98	0.961
0	20260130	18000	2030	236	0.272175	-5.90E-05	-0.022	98	0.961
0	20260130	18000	2035	167	0.404798	-0.0002	-0.05	98	0.961
0	20260130	18000	2040	105	0.667178	-0.00065	-0.097	98	0.961
0	20260130	18000	2045	52	1.349526	-0.00239	-0.177	98	0.961
0	20260130	18000	2050	15	4.134415	-0.00277	-0.067	98	0.961
0	20260130	19000	2025	311	0.19377	0	0	99	0.98
0	20260130	19000	2030	236	0.272199	2.40E-05	0.009	99	0.98
0	20260130	19000	2035	167	0.404862	6.40E-05	0.016	99	0.98
0	20260130	19000	2040	105	0.667609	0.000431	0.065	99	0.98
0	20260130	19000	2045	52	1.350591	0.001066	0.079	99	0.98
0	20260130	19000	2050	15	4.137112	0.002698	0.065	99	0.98
0	20260130	20000	2025	311	0.19377	0	0	99	0.98
0	20260130	20000	2030	236	0.272179	-2.00E-05	-0.007	99	0.98
0	20260130	20000	2035	167	0.404809	-5.40E-05	-0.013	99	0.98
0	20260130	20000	2040	105	0.66741	-0.0002	-0.03	99	0.98
0	20260130	20000	2045	52	1.350697	0.000106	0.008	99	0.98
0	20260130	20000	2050	15	4.136829	-0.00028	-0.007	99	0.98
1	20260131	1000	2025	311	0.19377				
1	20260131	1000	2030	236	0.272133				
1	20260131	1000	2035	167	0.405074				
1	20260131	1000	2040	105	0.667238				
1	20260131	1000	2045	52	1.345767				
1	20260131	1000	2050	15	4.11228				
1	20260131	2000	2025	311	0.19377	0	0	70	0.538
1	20260131	2000	2030	236	0.272105	-2.80E-05	-0.01	70	0.538
1	20260131	2000	2035	167	0.404569	-0.00051	-0.125	70	0.538
1	20260131	2000	2040	105	0.666337	-0.0009	-0.135	70	0.538
1	20260131	2000	2045	52	1.350578	0.004811	0.358	70	0.538
1	20260131	2000	2050	15	4.119689	0.007409	0.18	70	0.538
1	20260131	3000	2025	311	0.19377	0	0	72	0.562
1	20260131	3000	2030	236	0.272194	8.90E-05	0.033	72	0.562
1	20260131	3000	2035	167	0.404982	0.000413	0.102	72	0.562
1	20260131	3000	2040	105	0.667566	0.001229	0.184	72	0.562
1	20260131	3000	2045	52	1.352633	0.002055	0.152	72	0.562
1	20260131	3000	2050	15	4.160778	0.041089	0.997	72	0.562
1	20260131	4000	2025	311	0.19377	0	0	78	0.639
1	20260131	4000	2030	236	0.272271	7.80E-05	0.029	78	0.639
1	20260131	4000	2035	167	0.404556	-0.00043	-0.105	78	0.639
1	20260131	4000	2040	105	0.666469	-0.0011	-0.164	78	0.639
1	20260131	4000	2045	52	1.352345	-0.00029	-0.021	78	0.639
1	20260131	4000	2050	15	4.137439	-0.02334	-0.561	78	0.639

1	20260131	5000	2025	311	0.19377	0	0	86	0.754
1	20260131	5000	2030	236	0.272178	-9.30E-05	-0.034	86	0.754
1	20260131	5000	2035	167	0.404874	0.000318	0.079	86	0.754
1	20260131	5000	2040	105	0.667238	0.000769	0.115	86	0.754
1	20260131	5000	2045	52	1.350411	-0.00193	-0.143	86	0.754
1	20260131	5000	2050	15	4.146386	0.008947	0.216	86	0.754
1	20260131	6000	2025	311	0.19377	0	0	84	0.724
1	20260131	6000	2030	236	0.272214	3.60E-05	0.013	84	0.724
1	20260131	6000	2035	167	0.404887	1.30E-05	0.003	84	0.724
1	20260131	6000	2040	105	0.667734	0.000496	0.074	84	0.724
1	20260131	6000	2045	52	1.352247	0.001835	0.136	84	0.724
1	20260131	6000	2050	15	4.143488	-0.0029	-0.07	84	0.724
1	20260131	7000	2025	311	0.19377	0	0	85	0.739
1	20260131	7000	2030	236	0.272278	6.40E-05	0.023	85	0.739
1	20260131	7000	2035	167	0.404955	6.80E-05	0.017	85	0.739
1	20260131	7000	2040	105	0.667688	-4.60E-05	-0.007	85	0.739
1	20260131	7000	2045	52	1.349748	-0.0025	-0.185	85	0.739
1	20260131	7000	2050	15	4.124069	-0.01942	-0.469	85	0.739
1	20260131	8000	2025	311	0.19377	0	0	86	0.754
1	20260131	8000	2030	236	0.272109	-0.00017	-0.062	86	0.754
1	20260131	8000	2035	167	0.404939	-1.60E-05	-0.004	86	0.754
1	20260131	8000	2040	105	0.667581	-0.00011	-0.016	86	0.754
1	20260131	8000	2045	52	1.350195	0.000446	0.033	86	0.754
1	20260131	8000	2050	15	4.137412	0.013343	0.324	86	0.754
1	20260131	9000	2025	311	0.19377	0	0	90	0.818
1	20260131	9000	2030	236	0.27216	5.10E-05	0.019	90	0.818
1	20260131	9000	2035	167	0.404563	-0.00038	-0.093	90	0.818
1	20260131	9000	2040	105	0.6668	-0.00078	-0.117	90	0.818
1	20260131	9000	2045	52	1.351068	0.000873	0.065	90	0.818
1	20260131	9000	2050	15	4.124378	-0.01303	-0.315	90	0.818
1	20260131	10000	2025	311	0.19377	0	0	90	0.818
1	20260131	10000	2030	236	0.272172	1.20E-05	0.004	90	0.818
1	20260131	10000	2035	167	0.405194	0.000631	0.156	90	0.818
1	20260131	10000	2040	105	0.66822	0.00142	0.213	90	0.818
1	20260131	10000	2045	52	1.351752	0.000684	0.051	90	0.818
1	20260131	10000	2050	15	4.134921	0.010543	0.256	90	0.818
1	20260131	11000	2025	311	0.19377	0	0	91	0.835
1	20260131	11000	2030	236	0.272193	2.10E-05	0.008	91	0.835
1	20260131	11000	2035	167	0.405106	-8.80E-05	-0.022	91	0.835
1	20260131	11000	2040	105	0.667309	-0.00091	-0.136	91	0.835
1	20260131	11000	2045	52	1.350291	-0.00146	-0.108	91	0.835
1	20260131	11000	2050	15	4.142175	0.007254	0.175	91	0.835
1	20260131	12000	2025	311	0.19377	0	0	95	0.905

1	20260131	12000	2030	236	0.272133	-6.00E-05	-0.022	95	0.905
1	20260131	12000	2035	167	0.404884	-0.00022	-0.055	95	0.905
1	20260131	12000	2040	105	0.667317	8.00E-06	0.001	95	0.905
1	20260131	12000	2045	52	1.352878	0.002587	0.192	95	0.905
1	20260131	12000	2050	15	4.136283	-0.00589	-0.142	95	0.905
1	20260131	13000	2025	311	0.19377	0	0	94	0.887
1	20260131	13000	2030	236	0.272299	0.000166	0.061	94	0.887
1	20260131	13000	2035	167	0.405139	0.000256	0.063	94	0.887
1	20260131	13000	2040	105	0.667719	0.000403	0.06	94	0.887
1	20260131	13000	2045	52	1.350453	-0.00243	-0.179	94	0.887
1	20260131	13000	2050	15	4.140126	0.003843	0.093	94	0.887
1	20260131	14000	2025	311	0.19377	0	0	92	0.852
1	20260131	14000	2030	236	0.272205	-9.40E-05	-0.035	92	0.852
1	20260131	14000	2035	167	0.404868	-0.00027	-0.067	92	0.852
1	20260131	14000	2040	105	0.667518	-0.0002	-0.03	92	0.852
1	20260131	14000	2045	52	1.349716	-0.00074	-0.055	92	0.852
1	20260131	14000	2050	15	4.139462	-0.00066	-0.016	92	0.852
1	20260131	15000	2025	311	0.19377	0	0	93	0.869
1	20260131	15000	2030	236	0.272291	8.60E-05	0.032	93	0.869
1	20260131	15000	2035	167	0.405112	0.000244	0.06	93	0.869
1	20260131	15000	2040	105	0.667764	0.000246	0.037	93	0.869
1	20260131	15000	2045	52	1.352415	0.002699	0.2	93	0.869
1	20260131	15000	2050	15	4.139769	0.000307	0.007	93	0.869
1	20260131	16000	2025	311	0.19377	0	0	96	0.923
1	20260131	16000	2030	236	0.272183	-0.00011	-0.04	96	0.923
1	20260131	16000	2035	167	0.404774	-0.00034	-0.083	96	0.923
1	20260131	16000	2040	105	0.667373	-0.00039	-0.059	96	0.923
1	20260131	16000	2045	52	1.349633	-0.00278	-0.206	96	0.923
1	20260131	16000	2050	15	4.137167	-0.0026	-0.063	96	0.923
1	20260131	17000	2025	311	0.19377	0	0	94	0.887
1	20260131	17000	2030	236	0.272143	-3.90E-05	-0.015	94	0.887
1	20260131	17000	2035	167	0.404774	0	0	94	0.887
1	20260131	17000	2040	105	0.667453	8.00E-05	0.012	94	0.887
1	20260131	17000	2045	52	1.350746	0.001113	0.082	94	0.887
1	20260131	17000	2050	15	4.138311	0.001145	0.028	94	0.887
1	20260131	18000	2025	311	0.19377	0	0	96	0.923
1	20260131	18000	2030	236	0.272252	0.000108	0.04	96	0.923
1	20260131	18000	2035	167	0.404899	0.000125	0.031	96	0.923
1	20260131	18000	2040	105	0.667618	0.000165	0.025	96	0.923
1	20260131	18000	2045	52	1.350777	3.10E-05	0.002	96	0.923
1	20260131	18000	2050	15	4.13609	-0.00222	-0.054	96	0.923
1	20260131	19000	2025	311	0.19377	0	0	97	0.942
1	20260131	19000	2030	236	0.272198	-5.30E-05	-0.02	97	0.942

1	20260131	19000	2035	167	0.404784	-0.00012	-0.028	97	0.942
1	20260131	19000	2040	105	0.667351	-0.00027	-0.04	97	0.942
1	20260131	19000	2045	52	1.350462	-0.00032	-0.023	97	0.942
1	20260131	19000	2050	15	4.136709	0.00062	0.015	97	0.942
1	20260131	20000	2025	311	0.19377	0	0	98	0.961
1	20260131	20000	2030	236	0.272179	-1.90E-05	-0.007	98	0.961
1	20260131	20000	2035	167	0.404809	2.50E-05	0.006	98	0.961
1	20260131	20000	2040	105	0.66741	5.90E-05	0.009	98	0.961
1	20260131	20000	2045	52	1.350697	0.000235	0.017	98	0.961
1	20260131	20000	2050	15	4.136829	0.00012	0.003	98	0.961
2	20260132	1000	2025	311	0.19377				
2	20260132	1000	2030	236	0.2726				
2	20260132	1000	2035	167	0.405551				
2	20260132	1000	2040	105	0.666285				
2	20260132	1000	2045	52	1.347037				
2	20260132	1000	2050	15	4.156726				
2	20260132	2000	2025	311	0.19377	0	0	67	0.504
2	20260132	2000	2030	236	0.27263	2.90E-05	0.011	67	0.504
2	20260132	2000	2035	167	0.405665	0.000115	0.028	67	0.504
2	20260132	2000	2040	105	0.668086	0.001801	0.27	67	0.504
2	20260132	2000	2045	52	1.356666	0.009628	0.715	67	0.504
2	20260132	2000	2050	15	4.139214	-0.01751	-0.421	67	0.504
2	20260132	3000	2025	311	0.19377	0	0	71	0.55
2	20260132	3000	2030	236	0.271802	-0.00083	-0.304	71	0.55
2	20260132	3000	2035	167	0.403714	-0.00195	-0.481	71	0.55
2	20260132	3000	2040	105	0.6665	-0.00159	-0.237	71	0.55
2	20260132	3000	2045	52	1.347166	-0.0095	-0.7	71	0.55
2	20260132	3000	2050	15	4.138177	-0.00104	-0.025	71	0.55
2	20260132	4000	2025	311	0.19377	0	0	80	0.667
2	20260132	4000	2030	236	0.272339	0.000537	0.198	80	0.667
2	20260132	4000	2035	167	0.405226	0.001512	0.375	80	0.667
2	20260132	4000	2040	105	0.667524	0.001025	0.154	80	0.667
2	20260132	4000	2045	52	1.349074	0.001907	0.142	80	0.667
2	20260132	4000	2050	15	4.118583	-0.01959	-0.473	80	0.667
2	20260132	5000	2025	311	0.19377	0	0	85	0.739
2	20260132	5000	2030	236	0.272257	-8.20E-05	-0.03	85	0.739
2	20260132	5000	2035	167	0.40485	-0.00038	-0.093	85	0.739
2	20260132	5000	2040	105	0.668421	0.000897	0.134	85	0.739
2	20260132	5000	2045	52	1.352051	0.002977	0.221	85	0.739
2	20260132	5000	2050	15	4.136075	0.017492	0.425	85	0.739
2	20260132	6000	2025	311	0.19377	0	0	83	0.709
2	20260132	6000	2030	236	0.272138	-0.00012	-0.044	83	0.709
2	20260132	6000	2035	167	0.40527	0.000419	0.104	83	0.709

2	20260132	6000	2040	105	0.669048	0.000627	0.094	83	0.709
2	20260132	6000	2045	52	1.35275	0.000699	0.052	83	0.709
2	20260132	6000	2050	15	4.132871	-0.0032	-0.077	83	0.709
2	20260132	7000	2025	311	0.19377	0	0	85	0.739
2	20260132	7000	2030	236	0.272166	2.80E-05	0.01	85	0.739
2	20260132	7000	2035	167	0.404831	-0.00044	-0.108	85	0.739
2	20260132	7000	2040	105	0.667519	-0.00153	-0.229	85	0.739
2	20260132	7000	2045	52	1.348109	-0.00464	-0.343	85	0.739
2	20260132	7000	2050	15	4.141424	0.008553	0.207	85	0.739
2	20260132	8000	2025	311	0.19377	0	0	86	0.754
2	20260132	8000	2030	236	0.272261	9.50E-05	0.035	86	0.754
2	20260132	8000	2035	167	0.404884	5.20E-05	0.013	86	0.754
2	20260132	8000	2040	105	0.667319	-0.0002	-0.03	86	0.754
2	20260132	8000	2045	52	1.351956	0.003847	0.285	86	0.754
2	20260132	8000	2050	15	4.145188	0.003764	0.091	86	0.754
2	20260132	9000	2025	311	0.19377	0	0	88	0.786
2	20260132	9000	2030	236	0.272245	-1.60E-05	-0.006	88	0.786
2	20260132	9000	2035	167	0.404909	2.50E-05	0.006	88	0.786
2	20260132	9000	2040	105	0.666819	-0.0005	-0.075	88	0.786
2	20260132	9000	2045	52	1.351007	-0.00095	-0.07	88	0.786
2	20260132	9000	2050	15	4.136553	-0.00864	-0.208	88	0.786
2	20260132	10000	2025	311	0.19377	0	0	92	0.852
2	20260132	10000	2030	236	0.272379	0.000134	0.049	92	0.852
2	20260132	10000	2035	167	0.40499	8.10E-05	0.02	92	0.852
2	20260132	10000	2040	105	0.668195	0.001377	0.206	92	0.852
2	20260132	10000	2045	52	1.351609	0.000602	0.045	92	0.852
2	20260132	10000	2050	15	4.135175	-0.00138	-0.033	92	0.852
2	20260132	11000	2025	311	0.19377	0	0	90	0.818
2	20260132	11000	2030	236	0.272142	-0.00024	-0.087	90	0.818
2	20260132	11000	2035	167	0.404798	-0.00019	-0.047	90	0.818
2	20260132	11000	2040	105	0.667455	-0.00074	-0.111	90	0.818
2	20260132	11000	2045	52	1.350661	-0.00095	-0.07	90	0.818
2	20260132	11000	2050	15	4.129509	-0.00567	-0.137	90	0.818
2	20260132	12000	2025	311	0.19377	0	0	91	0.835
2	20260132	12000	2030	236	0.272184	4.20E-05	0.016	91	0.835
2	20260132	12000	2035	167	0.404941	0.000143	0.035	91	0.835
2	20260132	12000	2040	105	0.667009	-0.00045	-0.067	91	0.835
2	20260132	12000	2045	52	1.35054	-0.00012	-0.009	91	0.835
2	20260132	12000	2050	15	4.136491	0.006982	0.169	91	0.835
2	20260132	13000	2025	311	0.19377	0	0	95	0.905
2	20260132	13000	2030	236	0.272165	-1.90E-05	-0.007	95	0.905
2	20260132	13000	2035	167	0.404857	-8.40E-05	-0.021	95	0.905
2	20260132	13000	2040	105	0.667251	0.000241	0.036	95	0.905

2	20260132	13000	2045	52	1.349707	-0.00083	-0.062	95	0.905
2	20260132	13000	2050	15	4.133272	-0.00322	-0.078	95	0.905
2	20260132	14000	2025	311	0.19377	0	0	93	0.869
2	20260132	14000	2030	236	0.272275	0.00011	0.041	93	0.869
2	20260132	14000	2035	167	0.404856	0	0	93	0.869
2	20260132	14000	2040	105	0.66701	-0.00024	-0.036	93	0.869
2	20260132	14000	2045	52	1.349328	-0.00038	-0.028	93	0.869
2	20260132	14000	2050	15	4.134599	0.001327	0.032	93	0.869
2	20260132	15000	2025	311	0.19377	0	0	94	0.887
2	20260132	15000	2030	236	0.272151	-0.00012	-0.045	94	0.887
2	20260132	15000	2035	167	0.404672	-0.00018	-0.046	94	0.887
2	20260132	15000	2040	105	0.667213	0.000203	0.03	94	0.887
2	20260132	15000	2045	52	1.350852	0.001524	0.113	94	0.887
2	20260132	15000	2050	15	4.135256	0.000657	0.016	94	0.887
2	20260132	16000	2025	311	0.19377	0	0	95	0.905
2	20260132	16000	2030	236	0.272227	7.60E-05	0.028	95	0.905
2	20260132	16000	2035	167	0.404848	0.000176	0.044	95	0.905
2	20260132	16000	2040	105	0.667247	3.40E-05	0.005	95	0.905
2	20260132	16000	2045	52	1.350677	-0.00018	-0.013	95	0.905
2	20260132	16000	2050	15	4.131903	-0.00335	-0.081	95	0.905
2	20260132	17000	2025	311	0.19377	0	0	96	0.923
2	20260132	17000	2030	236	0.272149	-7.80E-05	-0.029	96	0.923
2	20260132	17000	2035	167	0.404872	2.40E-05	0.006	96	0.923
2	20260132	17000	2040	105	0.667414	0.000167	0.025	96	0.923
2	20260132	17000	2045	52	1.351843	0.001166	0.086	96	0.923
2	20260132	17000	2050	15	4.1401	0.008197	0.198	96	0.923
2	20260132	18000	2025	311	0.19377	0	0	94	0.887
2	20260132	18000	2030	236	0.2722	5.10E-05	0.019	94	0.887
2	20260132	18000	2035	167	0.404876	4.00E-06	0.001	94	0.887
2	20260132	18000	2040	105	0.667497	8.30E-05	0.012	94	0.887
2	20260132	18000	2045	52	1.350529	-0.00131	-0.097	94	0.887
2	20260132	18000	2050	15	4.134688	-0.00541	-0.131	94	0.887
2	20260132	19000	2025	311	0.19377	0	0	97	0.942
2	20260132	19000	2030	236	0.272116	-8.50E-05	-0.031	97	0.942
2	20260132	19000	2035	167	0.40479	-8.60E-05	-0.021	97	0.942
2	20260132	19000	2040	105	0.667474	-2.20E-05	-0.003	97	0.942
2	20260132	19000	2045	52	1.350851	0.000322	0.024	97	0.942
2	20260132	19000	2050	15	4.137474	0.002786	0.067	97	0.942
2	20260132	20000	2025	311	0.19377	0	0	99	0.98
2	20260132	20000	2030	236	0.272179	6.30E-05	0.023	99	0.98
2	20260132	20000	2035	167	0.404809	1.90E-05	0.005	99	0.98
2	20260132	20000	2040	105	0.66741	-6.50E-05	-0.01	99	0.98
2	20260132	20000	2045	52	1.350697	-0.00015	-0.011	99	0.98

2	20260132	20000	2050	15	4.136829	-0.00065	-0.016	99	0.98

APENDIX C:

Table C.1. Ranked Importance of All 311 Stations Based on Average Marginal Detour Impact

Rank	Station_ID	Avg_Marginal_Impact	Rank	Station_ID	Avg_Marginal_Impact	Rank	Station_ID	Avg_Marginal_Impact
1	841	0.174518441	121	565	0.09191785	241	151	0.058477787
2	259	0.166671536	122	1141	0.091860569	242	309	0.058464319
3	368	0.164677413	123	1038	0.091711071	243	1514	0.057676142
4	188	0.163215062	124	1374	0.091535063	244	1026	0.057043478
5	190	0.162653054	125	1226	0.09141239	245	215	0.05599909
6	922	0.157969834	126	184	0.090879625	246	594	0.05538659
7	265	0.154480777	127	365	0.090172558	247	689	0.054833803
8	338	0.154217555	128	46	0.08993838	248	218	0.054317416
9	231	0.152473587	129	41	0.08982911	249	156	0.053758363
10	400	0.152254235	130	654	0.089211137	250	660	0.053553967
11	643	0.150605064	131	456	0.088732918	251	1350	0.053398798
12	817	0.150362685	132	435	0.087829566	252	447	0.052714789
13	427	0.149370328	133	31	0.087436801	253	1122	0.052592824
14	183	0.148472693	134	130	0.086922738	254	1378	0.051735107
15	1117	0.147360331	135	343	0.086549325	255	1470	0.051238315
16	470	0.145195511	136	463	0.086467779	256	11	0.050758429
17	1074	0.14508473	137	791	0.086300227	257	1475	0.050035917
18	1515	0.141963822	138	878	0.0859215	258	168	0.049442112
19	443	0.141894592	139	863	0.085687782	259	280	0.049322614
20	232	0.141183989	140	481	0.08547344	260	701	0.04932259
21	915	0.137433924	141	631	0.085403476	261	1399	0.049220845
22	1023	0.135848409	142	301	0.085189415	262	1400	0.049167468
23	924	0.134953631	143	21	0.085122138	263	1046	0.048762669
24	1144	0.134843631	144	1134	0.084821604	264	1091	0.048214326
25	1053	0.134426269	145	452	0.084751069	265	268	0.046560211
26	532	0.134306712	146	975	0.084566001	266	1516	0.046342907
27	432	0.134192962	147	606	0.084470259	267	1489	0.045946115
28	623	0.133815954	148	1033	0.084278221	268	1066	0.04526076
29	639	0.132910791	149	314	0.084259261	269	330	0.044191835
30	1012	0.132461087	150	165	0.084012143	270	1376	0.044171059
31	1021	0.130618101	151	673	0.083146188	271	1390	0.042168353
32	529	0.130512325	152	460	0.082716284	272	155	0.038348224
33	478	0.130349418	153	1149	0.082234721	273	169	0.038208661
34	761	0.130037414	154	293	0.082189394	274	369	0.0373665
35	1079	0.129974897	155	581	0.082096472	275	933	0.037150062
36	844	0.129165356	156	1034	0.081874418	276	1364	0.03696209
37	760	0.12893912	157	1474	0.081613181	277	1469	0.03685416

38	120	0.128650195	158	389	0.081449534	278	1389	0.035128312
39	982	0.128392803	159	55	0.080576952	279	370	0.031747639
40	1150	0.127140364	160	266	0.080565149	280	1511	0.028571838
41	477	0.126592204	161	799	0.080435743	281	1418	0.026714015
42	554	0.126305348	162	111	0.079750927	282	170	0.024679133
43	1482	0.12517763	163	566	0.079374397	283	637	0.021885412
44	1073	0.124202362	164	471	0.079216111	284	498	0.017908356
45	1188	0.123494945	165	1014	0.078844742	285	206	0.016599531
46	397	0.123122201	166	876	0.078529901	286	537	0.016565304
47	1029	0.122444962	167	1101	0.078408766	287	26	0.015845869
48	355	0.122442802	168	1043	0.078260274	288	513	0.013818565
49	1411	0.121845935	169	1508	0.078185721	289	822	0.012501054
50	624	0.121640463	170	1187	0.078031547	290	17	0.012444689
51	951	0.12157847	171	530	0.077983696	291	622	0.012321112
52	600	0.120027223	172	578	0.077890787	292	250	0.008273283
53	485	0.119596088	173	940	0.077781084	293	1392	0.006931615
54	1108	0.119577094	174	620	0.077137915	294	1363	0.004272946
55	1175	0.119555252	175	1463	0.076634467	295	1121	0.003355225
56	1132	0.119280948	176	457	0.076547595	296	1125	0.003232222
57	1162	0.117624374	177	131	0.076539854	297	95	0.003150431
58	607	0.117533209	178	22	0.07651858	298	1172	0.002864423
59	455	0.117362451	179	1113	0.076084483	299	392	0.002828491
60	459	0.115791909	180	1063	0.075944714	300	224	0.002480939
61	353	0.115734209	181	275	0.075530065	301	356	0.002479379
62	1222	0.114041199	182	1052	0.074958089	302	322	0.002186431
63	450	0.113516701	183	386	0.074744373	303	492	0.00217768
64	1085	0.113487299	184	1120	0.074160256	304	1393	0.002031765
65	1077	0.113324398	185	413	0.073785885	305	907	0.001942391
66	1231	0.11283313	186	1487	0.073276143	306	123	0.001846112
67	858	0.11266091	187	1152	0.073030841	307	1176	0.001641863
68	1227	0.112526351	188	282	0.072987042	308	421	0.001493106
69	568	0.112272841	189	67	0.072874597	309	1123	0.001138045
70	464	0.111736102	190	20	0.07263193	310	360	0.001117833
71	569	0.111713325	191	278	0.07258762	311	509	0.000641608