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PUBLIC TRANSPORTATION TRANSITIONS TOWARD ZERO-EMISSION TECHNOLOGIES: A SYSTEMS THINKING APPROACH

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ABSTRACT: The decarbonization of public transit fleets is frequently approached as a technological replacement problem. However, growing evidence suggests that fleet transitions are better understood as wicked socio-technical problems shaped by interacting operational, economic, environmental, governance, and social factors. This paper develops a qualitative System Dynamics (SD) Causal Loop Diagram (CLD) that integrates 33 variables across five dimensions into eight feedback structures: four reinforcing loops, two balancing loops, and two causal chains. Building on a structured literature review, the framework introduces mechanisms of technological learning, institutional experience accumulation, supply chain maturity constraints, and political cycle disruptions that prior transit decarbonization models have not captured explicitly. Five system archetypes are identified: Limits to Growth, Shifting the Burden, Success to the Successful, Fixes that Fail, and Eroding Goals, which explain why agencies operating under comparable policy environments produce divergent transition outcomes. All variables are defined at a level suitable for Stock and Flow quantification and cross-city clustering analysis. The central finding is that transition outcomes are not determined by the inherent performance of any single powertrain technology but by the relative dominance of reinforcing and balancing feedback structures, which vary significantly across operating contexts.

1. INTRODUCTION

The transition to zero-emission public transit is typically framed both in engineering literature and in agency practice as a matter of selecting and deploying the right technology. Battery Electric Buses (BEBs) and Hydrogen Fuel Cell Buses (HFCBs) are evaluated through Total Cost of Ownership (TCO) models and Life Cycle Assessments (LCA), where the technology that performs best, under given assumptions, is recommended for its procurement. While this approach is useful, it has limitations. Evidence from different cities that have attempted large-scale fleet transitions shows that outcomes vary more than the technology-focused frameworks predict. Agencies that operate in similar policy environments, with access to comparable funding and targeting the same zero-emission bus (ZEB) technologies, have produced trajectories ranging from near-complete electrification to mixed-fleet operations with minimal ZEB penetration (Noto & Bianchi, 2015). This variability reflects the interaction of reinforcing and balancing feedback mechanisms across technical, operational, economic, governance, and social dimensions.

Recent studies of freight and transit decarbonization have shown that System Dynamics (SD) models are well-suited to represent the feedbacks, delays, and structural complexity that shape long-term transportation policy outcomes (Ghisolfi et al., 2022). This paper builds a CLD with 33 variables to incorporate institutional, learning, and political dynamics. The paper is structured as follows: Section 2 reviews the existing literature and variable selection, Section 3 details the methodology, Section 4 presents the CLD and dynamic hypotheses, Section 5 identifies and interprets the five system archetypes, Section 6 discusses planning and policy implications, and Section 7 concludes.

2. LITERATURE BACKGROUND

2.1 Five Systemic Dimensions

The complexity of transit fleet decarbonization requires a framework that goes beyond isolated technical parameters. Existing research shows that successful transitions depend on interactions across multiple domains that are often studied in isolation. Building on prior work in transit decarbonization, system-based analysis, and multi-level governance in transportation, this study organizes system variables into five interacting dimensions (Ghisolfi et al., 2022; Noto & Bianchi, 2015).

A holistic perspective is necessary to capture the causal dependencies across these dimensions. Technology performance defines the physical capabilities and limitations of the fleet, as factors such as battery degradation, energy density, and propulsion efficiency constrain vehicle range and reliability (Dindar et al., 2026; Peiretti Paradisi et al., 2025a). Operational feasibility translates these technical constraints into daily service provision, where route topology, scheduling requirements, and climate sensitivity, particularly range reduction under Canadian winter conditions, directly impact service reliability (Tian, Wang, et al., 2025). Economic and infrastructure constraints represent the financial and physical boundaries within which transit agencies operate; these include upfront capital investment, long-term operating costs, and the availability of grid capacity or fueling infrastructure required to support fleet-wide adoption (Sadrani et al., 2024). Environmental impacts capture life-cycle greenhouse gas (GHG) emissions, ensuring that tailpipe reductions are not offset by upstream energy production or manufacturing impacts (Deda et al., 2025; Kotagodahetti et al., 2024). Finally, governance and social dynamics represent the critical feedback between public policy, institutional decision-making, public acceptance, and perceived technology risk, which ultimately regulates the pace and stability of transition pathways (Barragán-Escandón et al., 2025; Rafew et al., 2024). Rather than reviewing individual powertrain technologies, these dimensions are used to structure the system-level analysis and to support the development of a qualitative SD model.

Table 1 summarizes the five dimensions and clarifies their roles within the system boundary of a transit agency. It distinguishes between endogenous decision levers, such as procurement and infrastructure investment, and exogenous constraints, including fuel price volatility and regional temperature variation.

Table 1: Dimensions and their role within the transit fleet decarbonization system

Dimension	Guiding Question	Role in the System
Technology Performance	Does the technology meet operational requirements?	Conditions operational capability
Operational Feasibility	Can scheduled service be reliably delivered?	Translates technical limits into service performance
Economic & Infrastructure	Is the transition financially and physically feasible?	Constrains investment and adoption decisions
Environmental Impact	What defines environmental performance over the life-cycle?	Generates the emissions signal that drives public and policy response
Governance & Social	Who decides, and under what pressures?	Accelerates or slows transition dynamics

2.2 Variable Selection

Variables included in the qualitative model were selected based on two criteria. First, they must be explicitly operationalized in existing transit decarbonization literature, either as decision variables, performance indicators, or system constraints. Second, they must be defined in a way that allows future quantification through data-driven equations or scenario-based assumptions. This approach ensures the CLD is directly scalable to a quantitative Stock and Flow model.

The variable set is built as follows. First, mechanisms of technological learning and cost reduction are incorporated through Learning Rate, Cumulative ZEB Units, and ZEB Unit Purchase Cost, capturing the economy-of-scale dynamics that have driven cost reductions in battery technology globally but that have not previously been modelled explicitly at the agency level (Matteson & Williams, 2015). Second, institutional and organizational capacity variables are introduced: Institutional Memory and Experience, Supply Chain Maturity, and Financial Health of Agency vary across agencies of similar size and budget and are among the strongest predictors of ZEB program success identified in state-of-practice reviews (Deliali et al., 2021; McCluskey et al., 2025). Third, governance dynamics variables, Political Stability, Electoral Cycle, and Governance Coordination, address the back-and-forth procurement patterns observed in politically contested environments that prior frameworks could not explain structurally (Yu et al., 2025). Table 2 presents the full variable set with definitions, SD types, and supporting references.

Table 2: Causal Loop Diagram (CLD) variables and definitions

No	Variable Name	Dimension	Short Definition	Reference
1	Average Bus Age	Technology Performance	The mean age of the fleet	(Noto & Bianchi, 2015; Talebi et al., 2025)
2	Bus Retirement Rate	Technology Performance	Annual rate at which ICE buses exit the fleet due to age/end-of-life (vehicles/year)	(Noto & Bianchi, 2015; Talebi et al., 2025)
3	Bus Fleet Inventory	Operational Feasibility	The total number of buses in active service across all powertrain types	(Othman et al., 2025; Talebi et al., 2025)
4	Charging/Refuelling Infrastructure Strain	Economic & Infrastructure	The strain of stations available to support operations	(R et al., 2024; Shehabeldeen & Mohamed, 2025; Varghese & Pradhan, 2025)
5	Cumulative ZEB Units	Technology Performance	Total cumulative number of ZEBs procured or operated by the agency to date (vehicles).	(Manzolli et al., 2025)
6	Electoral Cycle	Governance & Social	Timing and frequency of elections affecting infrastructure investment decisions (years to next election, election-year dummy).	(Yu et al., 2025)
7	External Temperature	Operational Feasibility	The ambient temperature that guides auxiliary energy demand	(Dindar et al. 2026; Peiretti Paradisi et al. 2025a; Tian, Wang et al. 2025)
8	Financial Health of Agency	Economic & Infrastructure	Composite indicator of agency solvency and fiscal space (operating margin, debt-service coverage, net income/revenue).	(Avenali et al., 2023; McCluskey et al., 2025)
9	Fleet Decarbonization Level	Environmental Impact	The percentage of the total fleet composed of zero-emission vehicles	(Talebi et al., 2025; Yeo et al., 2025)
10	Governance Coordination	Governance & Social	The level of alignment between authorities and utilities	(McCluskey et al., 2025; Noto & Bianchi, 2015)
11	Government Subsidies	Governance & Social	Financial support (grants, tax breaks) provided to offset high up-front costs	(Varghese and Pradhan 2025; Wang et al. 2025)
12	Grid Carbon Intensity	Environmental Impact	Amount of CO_2 emitted per unit of electricity generated in the local mix	(Basuki, 2025; Y. Wang et al., 2025)
13	ICE Fleet Stock	Technology Performance	Number of ICE buses (diesel, CNG, hybrid) currently in service (vehicles).	(Avenali et al., 2023; Talebi et al., 2025)

14	ICE Procurement Rate	Governance & Social	Annual rate at which new ICE buses are added to the fleet (vehicles/year or % of total procurements).	(Talebi et al., 2025)
15	Institutional Memory & Experience	Governance & Social	Accumulated years of ZEB operation (sum of ZEB-years in service) or years since first ZEB deployment.	(Deliali et al., 2021; McCluskey et al., 2025)
16	Investment Capacity	Economic & Infrastructure	Maximum capital mobilizable for fleet and infrastructure investments per year (budget or borrowing headroom).	(Basuki, 2025; Dindar et al., 2026; Varghese & Pradhan, 2025)
17	Learning Rate	Economic & Infrastructure	Percentage reduction in ZEB or battery unit cost per doubling of cumulative deployed capacity (% per doubling, Wright's Law).	(Manzolli et al., 2025; Matteson & Williams, 2015)
18	Life-cycle GHG Emissions	Environmental Impact	Total life-cycle emissions	(Lubecki et al., 2025; Mahmoudi et al., 2025)
19	Perceived Technology Risk	Governance & Social	Subjective assessments of potential failure rates and long-term viability	(Sadrani et al., 2024)
20	Policy Mandates & Targets	Governance & Social	Legislative requirements or climate goals that drive the adoption	(Frieß & Pferschy, 2024; Talebi et al., 2025)
21	Political Stability	Governance & Social	Stability of the political and regulatory environment over the planning horizon (governance indices, risk of policy reversal).	(Yu et al., 2025)
22	Procurement Capital (CAPEX)	Economic & Infrastructure	Total upfront investment required for vehicles, batteries, and infrastructure	(Basuki 2025; Shehabeldeen and Mohamed 2025; Wang et al. 2025)
23	Public Acceptance	Governance & Social	Social and passenger perception (service quality and environmental benefits)	(Cabigiosu, 2025; Estrada Poggio et al., 2023; Talebi et al., 2025)
24	Real-World Operational Range	Technology Performance	The effective distance a bus can travel on a single charge/refuel	(Sadrani et al., 2024; Tian, Zhai, et al., 2025)
25	Ridership & Transit Demand	Operational Feasibility	Total annual passenger trips or passenger-km, and/or peak-hour loads on key corridors.	(Basuki, 2025; Noto & Bianchi, 2015)
26	Service Reliability	Operational Feasibility	Ability to complete scheduled trips without interruptions	(Hu et al., 2025; McCluskey et al., 2025; Noto & Bianchi, 2015)
27	Spare Vehicle Ratio	Operational Feasibility	The buffer of additional buses required to maintain service	(Bartłomiejczyk & Caliandro, 2025; Basuki, 2025; McCluskey et al., 2025)
28	Supply Chain Maturity	Economic & Infrastructure	Reliability and diversity of ZEB component suppliers — average lead times and number of qualified local suppliers (composite index).	(Bastos et al., 2025; Manzolli et al., 2025; Rodrigues et al., 2025)
29	Total Cost of Ownership (TCO)	Economic & Infrastructure	The life-cycle sum of CAPEX and OPEX	(Chen & Wang, 2024; Dindar et al., 2026; McCluskey et al., 2025)
30	Vehicle Energy Efficiency	Technology Performance	The technology-specific energy consumption per kilometre	(Dindar et al., 2026; Talebi et al., 2025; Tian, Wang, et al., 2025)

31	ZEB Fleet Stock	Technology Performance	Number of zero-emission buses currently in service (vehicles)	(McCluskey et al., 2025; Talebi et al., 2025)
32	ZEB Procurement Rate	Governance & Social	The annual rate at which new ZEBs are added to the fleet	(Talebi et al., 2025)
33	ZEB Unit Purchase Cost	Economic & Infrastructure	Purchase price per zero-emission bus (and associated depot hardware), in currency per vehicle	(Avenali et al., 2023; Varghese & Pradhan, 2025)

Note: All variables are defined at a level suitable for qualitative causal modelling and future quantitative parameterization.

3. METHODOLOGY

3.1 System Boundary and Assumptions

The system boundary is set at the transit agency level. This boundary is selected because the primary decision-making processes related to vehicle procurement, budget allocation, maintenance planning, and infrastructure deployment are managed within the agency's operational and institutional control. Considering this boundary, endogenous variables represent internal decisions and accumulations such as fleet stocks, procurement rates, infrastructure strain, and institutional experience. Exogenous drivers represent external conditions that constrain or shape agency decisions but are not directly controlled by the agency. These include regional temperature variation, grid carbon intensity, and electoral cycles (Rafew et al., 2024). Governance Coordination occupies a hybrid position: it is treated as a policy lever that can be adjusted through external institutional design, but whose effects propagate endogenously through the system.

Several simplifying assumptions are required to keep conceptual clarity at this qualitative stage. Operating Expense (OPEX) is absorbed into TCO, assuming that the CAPEX/OPEX ratio is relatively stable within each technology type over the planning horizon. Traffic Congestion is absorbed into vehicle energy efficiency as a modifier of context. Battery State of Health degradation is captured implicitly through its effect on OPEX. Supply Chain Maturity operates as an explicit variable in B2, capturing how supplier diversity and lead times constrain procurement costs. Its connection to Service Reliability is not modelled as a direct link to avoid visual noise in the CLD, but it is acknowledged that mature supply chains improve operational continuity. Similarly, Average Bus Age is treated as evolving independently of short-term procurement decisions within this qualitative structure; the reinforcing effect of new ICE (or ZEB) procurement on fleet age composition is acknowledged but not modelled as an explicit feedback link at this stage, and is flagged for resolution in the quantitative Stock and Flow structure. In addition, to maintain conceptual clarity for this qualitative analysis, the fleet is represented using two aggregate stocks: the Zero-Emission Bus (ZEB) fleet (including battery electric, hydrogen fuel cell, and trolley/in-motion powertrain technologies) and the Internal Combustion Engine (ICE) fleet (including diesel, hybrid, and CNG/bio-CNG powertrain technologies).

This stock-and-flow structure, a fundamental structure in SD used to capture accumulation and depletion processes, is a high-level abstraction intended to highlight the system-wide trade-offs rather than technology-specific optimization. It is important to highlight that the framework does not assume a 100% transition to ZEB fleets. Instead, it allows for transition pathways in which ICE vehicles may persist in the fleet stock depending on contextual constraints. This assumption reflects evidence from transit agencies where mixed fleets remain a rational outcome under certain operating conditions. This framework introduces two additional implicit stocks: Cumulative ZEB Units, which drives the learning rate dynamic, and Institutional Memory and Experience, which accumulates with operational history and reduces perceived technology risk over time.

3.2 CLD Building Process

The Causal Loop Diagram was developed in Vensim software following a structured process: (i) defining systemic dimensions, (ii) identifying key variables within each dimension based on literature evidence of operationalization and quantification, (iii) assigning causal links, polarities and delays (if applicable) based on literature-validated mechanisms, (iv) identification of reinforcing and balancing feedback loops, and causal chains, (v) validate loop types by multiplying polarity products, and (vi) examine the structures identifying SD archetypes, following the canonical typology of Senge (1990) as systematized by Braun (2002).
Causal polarities follow the standard SD rules: a positive polarity (+) indicates variables move in the same direction, a negative polarity (-) indicates inverse movement, holding other factors constant. Delays are marked on the links using a double-bar notation (||). Exogenous variables enter the CLD through dashed arrows. The loop type of each feedback structure was verified by multiplying all link polarities: a positive product confirms a reinforcing loop, a negative product confirms a balancing loop. Causal chains were verified by confirming that at least one endpoint is exogenous and receives no return link from inside the system. Each feedback structure was assigned a distinct colour in the CLD to support readability: light blue for R1, purple for R2, dark green for R3, brown for R4, light red for B1, pink for B2, light green for CC1 and blue-purple for CC2. Variables and links shared across multiple structures are shown in red.

4. SYSTEM STRUCTURE AND DYNAMIC HYPOTHESES

The CLD integrates 33 variables across five dimensions into a structure organized around two main stocks: ZEB Fleet Stock and ICE Fleet Stock, and eight feedback structures: four reinforcing loops (R1-R4), two balancing loops (B1-B2), and two Causal Chains (CC1-CC2). Two additional implicit stocks accumulate over time and drive key mechanisms: Cumulative ZEB Units activate the learning rate, and Institutional Memory and Experience reduce perceived technology risk. Supply Chain Maturity develops as cumulative procurement scales local supplier networks. The CLD architecture follows the behaviour where technology performance conditions the operational feasibility, which in turn shapes economic outcomes, which feed governance and social dynamics, which then loop back to regulate the procurement decisions.

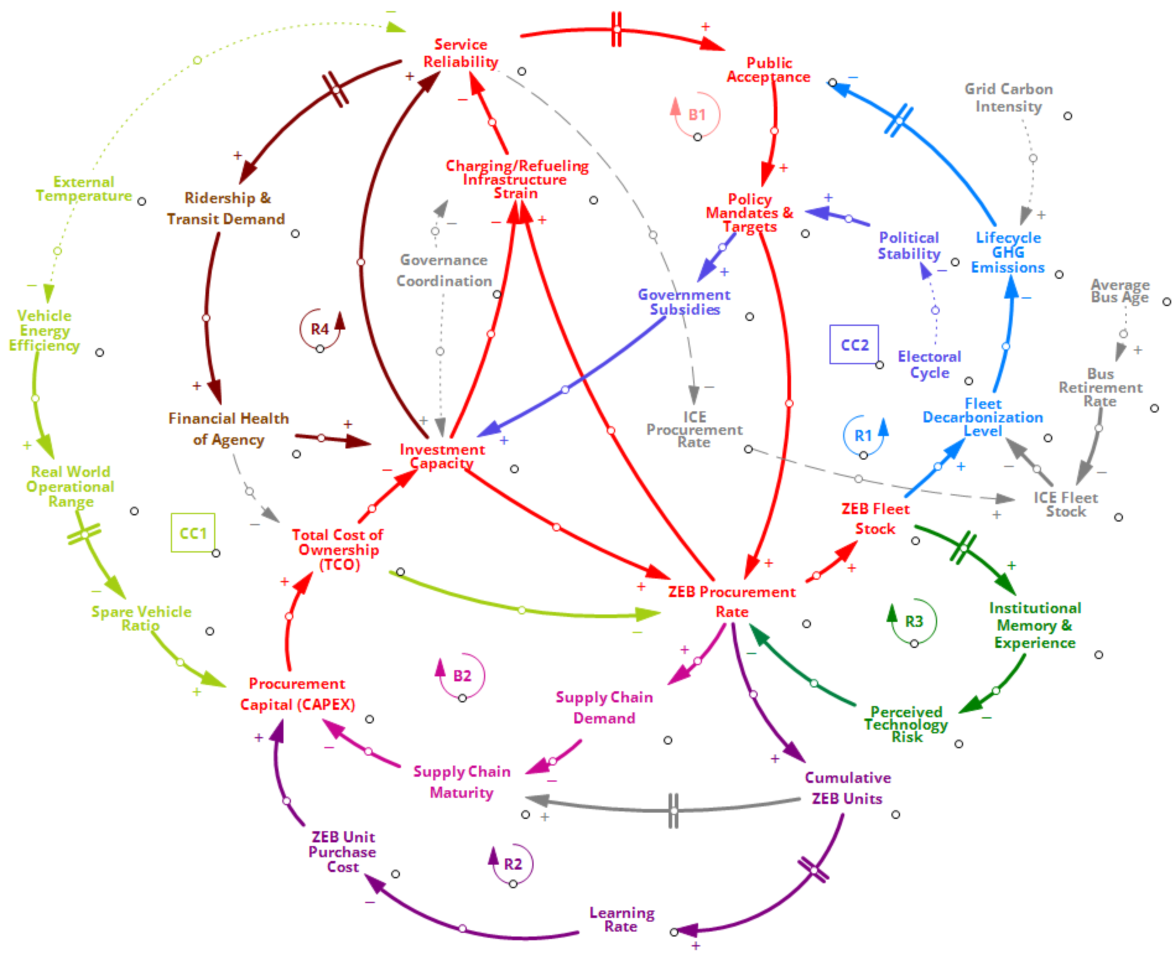

Figure 1: Qualitative Causal Loop Diagram (CLD) of transit fleet decarbonization at the transit agency level. Arrows indicate causal influence; "+" denotes variables move in the same direction and "–" denotes inverse movement, holding other factors constant. Double-bar notation (||) indicates time delays. Dashed arrows indicate exogenous inputs. Colour coding corresponds to feedback structures as described in Section 3.2

Each feedback structure has a dynamic hypothesis, an explanation of the structure that constitutes a pattern of behaviour that is observed or is expected during the transit fleet transition. Table 3 summarizes all eight structures with their core mechanism and expected behaviour. The explanation below develops the most important mechanisms

4.1 R1: Decarbonization Momentum (Reinforcing)

Higher ZEB Procurement Rate increases ZEB Fleet Stock, raising Fleet Decarbonization Level and reducing Lifecycle GHG Emissions. Over a delay, visible emission reductions strengthen Public Acceptance and reinforce Policy Mandates and Targets, accelerating further procurement. Polarity product: (+)(+)(−)(−)(+)(+) = (+). This loop explains take-off behaviour in jurisdictions with early ZEB outcomes and clean grids. Its vulnerability is the perception delay, and its sensitivity to Grid Carbon Intensity. In high-carbon grid regions, emission reductions are smaller, and the environmental signal feeding back into public and political support is weaker. It is important to note that Lifecycle GHG Emissions is sensitive to two exogenous inputs: Grid Carbon Intensity, which modulates the well-to-wheel emission factor of ZEBs, and the fleet composition mix captured by Fleet Decarbonization Level. A shift in either variable, for example, a cleaner grid or a faster ZEB adoption rate, directly changes the emission signal feeding back into Public Acceptance, altering the strength of R1. This sensitivity makes R1 context-dependent: the same procurement rate produces stronger political momentum in a low-carbon grid region than in a high-carbon one.

4.2 R2: Economy of Scale Loop (Reinforcing)

Each ZEB procured contributes to Cumulative ZEB Units, which activates the Learning Rate after a delay following Wright's Law. The declining ZEB Unit Purchase Cost reduces CAPEX and TCO, freeing Investment Capacity for further procurement. Polarity product: (+)(+)(−)(+)(+)(−)(+) = (+). This loop creates a structural cost advantage for early adopters, agencies that procure first accumulate learning faster, reducing their unit costs ahead of late adopters. This mechanism provides a structural explanation for why agencies with similar budgets diverge over time.

4.3 R3: Institutional Learning Loop (Reinforcing)

As ZEB Fleet Stock accumulates, agencies build Institutional Memory and Experience through operational exposure with a delay. This experience reduces Perceived Technology Risk among decision-makers, enabling more ambitious procurement. Polarity product: (+)(−)(−) = (+). This loop explains why agencies with prior pilot programs procure more confidently in subsequent cycles, not because the technology changed, but because organizational familiarity reduced uncertainty (Deliali et al., 2021; Sadrani et al., 2024).

4.4 R4: Revenue Loop (Reinforcing)

Service Reliability drives Ridership and Transit Demand with a delay, generating fare revenue that improves the Financial Health of the Agency and expands Investment Capacity. Investment Capacity reduces Charging/Refuelling Infrastructure Strain, closing the loop back to Service Reliability, representing how financial capacity funds the infrastructure and maintenance capacity that sustains service performance (McCluskey et al., 2025). Polarity product: (+)(+)(-)(-)(+) = (+). This loop connects service quality directly to the financial sustainability of the transition, making reliability management a financial as well as an operational priority.

4.5 B1: Operational Reliability Constraint (Balancing)

Rapid growth in ZEB Procurement Rate pressures charging and Refuelling Infrastructure, reducing Service Reliability when infrastructure does not scale proportionally. Declining reliability erodes Public Acceptance, weakening Policy Mandates and slowing procurement. Polarity product: (+)(−)(+)(+)(+) = (−). Governance Coordination is the structural intervention that breaks this loop by ensuring infrastructure is commissioned before strain appears. This loop is the main explanation for the stagnation at 20 to 30 percent ZEB penetration documented across multiple North American and European agencies.

4.6 B2: Supply Chain Constraint (Balancing)

ZEB Procurement Rate increases Supply Chain Demand for vehicles, batteries, and components. When this demand outpaces Supply Chain Maturity, measured by supplier diversity and lead times, Procurement Capital rises as agencies face longer waits and higher prices from constrained suppliers. Higher CAPEX raises TCO, slowing further procurement. Supply Chain Maturity itself improves over time as Cumulative ZEB Units grow, activating local supplier networks with a delay of two to four years. Polarity product: (+)(−)(−)(+)(+)(−) = (−) — Balancing confirmed. Unlike B1 where the constraint is physical infrastructure, here the constraint is market and logistics readiness. This loop connects with R2: as Supply Chain Maturity improves, it reinforces the cost-reduction pathway alongside Learning Rate.

4.7 CC1: Range-Cost Offset (Causal Chain)

Cold External Temperature reduces Vehicle Energy Efficiency by increasing auxiliary heating and thermal management loads, shrinking Real-World Operational Range and requiring a larger Spare Vehicle Ratio. Additional vehicles raise CAPEX and TCO, reducing ZEB Procurement Rate. This chain does not close because the external temperature is exogenous. Its effect is permanent and asymmetric: BEBs are disproportionately affected relative to hydrogen or hybrid technologies, which has direct implications for technology selection in cold-climate contexts like Canada. Beyond the cost pathway described in CC1, External Temperature also directly reduces Service Reliability through battery failures, extended charging times, and operational disruptions under extreme cold, creating a second negative pressure on the system that does not depend on the range-cost mechanism.

4.8 CC2 — Electoral Cycle Interrupt (Causal Chain)

The Electoral Cycle introduces a periodic perturbation, approximately every four years, that reduces Political Stability, weakening Policy Mandates, Government Subsidies, and Investment Capacity. This chain does not close because the Electoral Cycle is exogenous, driven by an external clock rather than system state. Its primary effect is to generate stop-and-go procurement patterns in jurisdictions where ZEB programs are politically contingent, and to explain why agencies under stable political environments achieve more consistent trajectories.

Table 3: Feedback Loops and Causal Chains

Structure ID	Name	Type	Core Mechanism	Expected Behaviour
R1	Decarbonization Momentum	Reinforcing	ZEB adoption reduces GHG → strengthens public acceptance and policy → accelerates procurement	Take-off after credible environmental outcomes; weakened by high grid carbon intensity
R2	Economy of Scale	Reinforcing	Cumulative units activate learning rate → reduces unit cost → lowers TCO → frees investment capacity.	Cost-driven acceleration; early adopters gain a structural advantage over late movers
R3	Institutional Learning	Reinforcing	Operational experience → reduces perceived risk → enables more ambitious procurement	Confidence-driven acceleration; agencies with pilot history procure faster in subsequent cycles
R4	Revenue Loop	Reinforcing	Reliability → ridership → financial health → investment capacity → reliability	Reliability management is a financial as well as an operational priority
B1	Operational Reliability Constraint	Balancing	Rapid deployment strains infrastructure → reduces reliability → weakens acceptance and slows procurement	Plateau at 20-30% ZEB; Governance Coordination breaks this loop
B2	Supply Chain Constraint	Balancing	Procurement growth outpaces supply chain maturity → raises CAPEX → increases TCO → slows procurement	Skill-gap-driven stalling → Supply-chain-driven cost pressure; activates in parallel with R2 during rapid deployment
CC1	Range-Cost Offset	Causal Chain	Cold climate reduces efficiency → lowers range → increases spare ratio and CAPEX → raises TCO → weakens procurement	Permanent cost penalty in cold-climate contexts; BEBs disproportionately affected
CC2	Electoral Cycle Interrupt	Causal Chain	Electoral transitions reduce political stability → weaken policy mandates and subsidies → constrain investment	Periodic stop-and-go procurement patterns in politically contested environments

Note: Structure descriptions are qualitative and indicate expected system tendencies; quantitative magnitudes depend on future parameterization.

5. SYSTEM ARCHETYPES

System archetypes are recurring structural patterns in feedback systems that generate characteristic modes of behaviour. Identifying archetypes in a CLD connects the model to established systems thinking theory and provides decision-makers with recognizable templates for anticipating transition dynamics. Five archetypes are identified in the CLD structure.

Table 4: System Archetypes

Archetype	Loops Involved	Mechanism	Policy Implication
Limits to Growth	R1+R2+R3+R4 vs. B1+B2	Adoption accelerates through four reinforcing loops but stalls when infrastructure strain (B1) and supply chain constraints (B2) raise costs and reduce reliability faster than governance can respond	Invest in infrastructure before fleet grows, not after problems arise
Shifting the Burden	B1 active + ICE persistence	When B1 activates, agencies redeploy ICE buses as a temporary fix. This relieves immediate pressure but reduces urgency around resolving the infrastructure deficit, supporting ICE dependence	Address the infrastructure deficit directly rather than buffering with ICE backup vehicles
Success to the Successful	R2+R3 favouring early adopters	Economy of Scale and Institutional Learning loops create cumulative cost and knowledge advantages for agencies that procured first. Late transitioners face the same costs without the organizational readiness	Early procurement yields compounding returns; waiting has a structural cost beyond the financial one
Fixes that Fail	CC2 disrupting R1	Subsidies support CAPEX in the short term. When CC2 activates, and political transitions cut mandates and subsidies, agencies without internal Investment Capacity cannot sustain procurement momentum	Build endogenous investment capacity rather than subsidy dependency
Eroding Goals	B1+B2 simultaneously active	Compounding reliability failures leads agencies to quietly lower procurement ambitions rather than resolving root causes. Targets erode silently without explicit policy reversal	Requires simultaneous resolution of both constraints through proactive Governance Coordination

Note: Structure descriptions are qualitative and indicate expected system tendencies; quantitative magnitudes depend on future parameterization.

The Limits to Growth archetype is the system's most basic pattern. The four reinforcing loops lead to a fast ZEB adoption, which eventually activates B1 and B2 when infrastructure and supply chains do not scale at the same rate. This explains why ZEB penetration has been stuck at 20 to 30 percent for a long time: not because the technology fails, but because the conditions in the supporting system have not kept pace. The policy implication is clear: investing in infrastructure and supply chain readiness before the fleet grows is better than waiting until the problems arise.

When B1 activates, agencies redeploy ICE buses as a temporary fix, and the Shifting the Burden archetype emerges. This takes some of the pressure off immediate service, but reduces the urgency of resolving the infrastructure deficit, meaning ICE dependence will continue even after its planned retirement date. This pattern is especially relevant in Canadian contexts where CC1 puts more pressure on ICE retention costs.

The Success to the Successful archetype explains cross-agency divergence. Loops R2 and R3 give early adopters cumulative benefits by lowering unit costs and boosting institutional confidence. Late transitioners face the same costs without the organizational readiness, making their early experiences harder and reinforcing the decision to delay further. The structural gap between early and late adopters grows over time, regardless of the policy environment.

The Fixes that Fail archetype explains paths that go back and forth. Subsidies fix CAPEX in the short term, but when they are tied to electoral cycles, they fail when political changes cut mandates and funding. Agencies that relied on external subsidies rather than building internal Investment Capacity cannot sustain momentum after the fix is taken away.

The Eroding Goals archetype happens when B1 and B2 activate at the same time. Agencies quietly lower their procurement goals instead of fixing the root causes of reliability failures. Policy mandates are softened, then targets are extended, and the original decarbonization goal erodes without an explicit reversal. This pattern is most likely in agencies where Governance Coordination is not enough to quickly fix both infrastructure and supply chain constraints at the same time.

6. DISCUSSION

6.1 Why Similar Agencies Diverge

The main finding of this analysis is that the differences in fleet decarbonization outcomes across transit agencies are not due to differences in ZEB technology performance, funding levels, or policy ambition. It is a function of which feedback loops dominate in a given context. In cold-climate regions with high grid carbon intensity, CC1 and a weakened R1 combine to make the economic and environmental case for ZEB procurement less clear. In agencies with shallow institutional histories and limited supply chain development, B2 activates early, limiting reliability and eroding the political support that R1 requires to sustain momentum. In politically volatile environments, CC2 creates procurement problems that prevent R2 and R3 from accumulating the learning and experience required for self-sustaining momentum.

This structural perspective reframes the planning question. Rather than asking which technology is best, planners and policymakers should ask: which feedback loops are likely to dominate in our context, and what governance and investment strategies are required to prevent constraining loops from prematurely limiting growth? The answer will differ across cities, which is the motivation for the cross-city clustering analysis that this framework is designed to support.

6.2 Governance Coordination as the Primary Leverage Point

Across all five archetypes, Governance Coordination emerges as the variable most capable of simultaneously weakening the balancing loops (B1, B2) and strengthening the reinforcing loops (R1, R4). Effective coordination between transit agencies, electric utilities and municipal government enables infrastructure to scale ahead of vehicle deployment, supply chains to develop in parallel with fleet expansion, and public trust to be maintained through well-managed service improvements. The framework suggests that infrastructure investment and supply chain development are not simply cost items; they are conditions under which reinforcing momentum becomes self-sustaining. Agencies that treat them as secondary to vehicle procurement systematically underinvest in the structural enablers of transition.

6.3 Implications for Cross-City Clustering

The extended variable set provides a validated basis for cross-city clustering of transit agency decarbonization trajectories. The variables most suitable as clustering dimensions — those that vary systematically across cities and are causally linked to which loops dominate — are: External Temperature, Grid Carbon Intensity, Fleet Decarbonization Level, Financial Health of Agency, Governance Coordination, Institutional Memory and Experience, Total Cost of Ownership, and Policy Mandates and Targets. These eight variables correspond directly to the structural positions in the CLD where contextual variation most strongly determines loop dominance, providing a theory-grounded basis for cluster formation rather than a purely empirical one.

6.4 Validation Status and Limitations

The structural validity of the CLD was assessed through polarity-product verification for each feedback structure (Section 3.2), confirming internal consistency between link polarities and loop classification. However, this qualitative model has not yet undergone structural or behavioral validation with domain experts, following the multi-stage approach outlined by Barlas (1996) and Forrester & Senge (1980). Content validation, confirming that the causal mechanisms reflect the judgment of transit planners, utility representatives, and policymakers, is planned through Group Model Building workshops as a subsequent step (see Section 7). Until this validation is complete, the causal structure and archetype interpretations presented here should be read as a literature-grounded hypothesis rather than an empirically confirmed system representation.

7. CONCLUSIONS

This paper presents a qualitative System Dynamics framework for transit fleet decarbonization, organized around a CLD with 33 variables and eight feedback structures: four reinforcing loops, two balancing loops, and two causal chains. The framework incorporates mechanisms of technological learning, institutional experience accumulation, supply chain constraints, and political cycle disruptions. Five system archetypes are identified that explain the divergence in the transition outcomes across agencies operating under similar policy environments.

The central finding is that transition outcomes are not determined by the superiority of any powertrain technology. They emerge from the relative dominance of reinforcing and balancing feedback structures, which are shaped by contextual factors including: climate, grid carbon intensity, institutional history, supply chain readiness, and political continuity. Governance Coordination is identified as the primary leverage point, the variable most capable of simultaneously enabling reinforcing momentum and preventing the premature activation of balancing constraints.

The qualitative CLD is constructed at a level of abstraction suitable for quantitative translation. All 33 variables are defined with measurement units or index specifications compatible with a Stock and Flow model, and the full causal link structure provides the foundation for future parameterization. Future work will develop a quantitative Stock and Flow model from this structure, enabling scenario-based analysis across city clusters defined by the clustering dimensions identified in Section 6.3. Validation through Group Model Building workshops with transit agency planners, utility representatives, and policy makers is planned as a subsequent step. Several factors, including equity impacts, demand elasticity, and technology-specific sub-stock differentiation, were intentionally excluded to maintain conceptual clarity but remain structurally compatible with future model extensions.

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