A System Dynamics Framework for Sustainable Transportation Planning; Policy Implications for Low-Carbon Urban Development

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Abstract: This paper introduces a system dynamics (SD) and geographic information systems (GIS) framework for evaluating the sustainability of urban transportation policies. The framework emphasizes the integration of dynamic feedback modeling with spatial metrics such as density, land-use diversity, parking supply, and transit accessibility. Building on a review of existing literature, we outline the conceptual structure of an SD–GIS approach that links urban form and travel behavior to long-term sustainability outcomes. While no detailed case studies are presented here, the framework is designed to be adaptable to redevelopment contexts, where decisions on parking and transit-oriented development (TOD) play a pivotal role. This work represents preliminary findings, which were later expanded and validated with case study applications in subsequent research. The paper demonstrates how SD–GIS integration can support policymakers in identifying feedback-driven, location-sensitive strategies for reducing car dependency and advancing sustainable mobility.

1. Introduction

Urbanization has accelerated rapidly in recent decades, posing significant challenges for sustainable transportation planning (May, 2013; Shah et al., 2021). As cities expand, the interplay between urban form and travel behavior becomes increasingly complex, influencing accessibility, mode choice, and environmental outcomes (Chang, 2006; Zahabi et al., 2012). Transit-Oriented Development (TOD) has emerged as a widely endorsed strategy to reduce car dependency by promoting compact, mixed-use, and walkable neighborhoods centered around high-capacity transit infrastructure (Langlois et al., 2015; Newman, 2007). However, the effectiveness of TOD and other sustainable transportation strategies depends on a comprehensive understanding of how urban form interacts with transportation policies (Handy, 1996).

System Dynamics Modeling (SDM) has been instrumental in capturing the dynamic, feedback-driven nature of urban systems, allowing for the simulation of policy interventions over time (Ercan, 2016). Yet, conventional SDM approaches often lack spatial features, limiting their ability to account for geographic variations in land use, transit accessibility, and infrastructure availability. On the other hand, Geographic Information Systems (GIS) provide essential spatial insights but are seldom integrated into system dynamics frameworks. This disconnect restricts the capacity of planners to develop data-driven, location-sensitive strategies that optimize urban mobility and sustainability (Karjalainen & Juhola, 2021). The lack of an integrated approach that considers both system dynamics and spatial attributes in transportation modeling remains a fundamental gap in urban planning research.

To address this gap, this study develops an integrated System Dynamics-GIS framework for assessing the sustainability of urban transportation systems. By integrating GIS-based spatial metrics into SDM, this approach enhances traditional system dynamics modeling by incorporating location-based variables. The framework is designed to evaluate key policy interventions, including TOD strategies and parking regulations, which play a critical role in shaping travel behavior (Ercan, 2016; Kennedy et al., 2005; Newman, 2007). Parking supply, in particular, remains an underexplored yet powerful determinant of vehicle ownership and mode choice, influencing the extent to which cities can transition away from car dependence (Albalate & Gragera, 2020; Yan et al., 2019). This research applies the proposed framework to two case studies in Montreal, Bridge-Bonaventure and Lachine-Est, both undergoing brownfield redevelopment with a focus on sustainable mobility. Through scenario simulations, this study examines how variations in density distribution, transit investment, and parking policies influence travel behavior, vehicle ownership, and greenhouse gas (GHG) emissions. By incorporating both dynamic system feedback and spatial features, the proposed framework offers a more comprehensive understanding of how urban form and transportation policies interact to support sustainable development.

2. Literature Review

Efforts to create more sustainable urban transportation systems have gained momentum in recent decades, driven by growing concerns about traffic congestion, air pollution, and rising greenhouse gas emissions (Belzer & Autler, 2002; Miller et al., 2016). Initially, urban development patterns were characterized by suburban sprawl, which encouraged extensive car use and created long travel distances (Knowles et al., 2020; Suzuki et al., 2013). In the late twentieth century, researchers and policymakers began to advocate for strategies like “smart growth” and “new urbanism,” emphasizing compact, walkable neighborhoods with mixed land uses and access to transit (Belzer & Autler, 2002; Knowles et al., 2020; Krizek, 2003; Padeiro et al., 2019). These movements aimed to reduce reliance on cars, promote public transit, and encourage more walking and cycling (Campos Ferreira et al., 2022; Cervero & Sullivan, 2011; Ibraeva et al., 2020; Krizek, 2003; Padeiro et al., 2019). Over time, additional frameworks emerged; like TOD and the complete streets concept, aiming to design more livable cities by organizing growth around transportation hubs (Knowles et al., 2020; Loo & du Verle, 2017). While these approaches have pushed the conversation on sustainable mobility forward, the complexity of urban environments still poses challenges for planners and researchers which underscores the need for integrated models and tools that account for the many factors shaping travel behavior across both time and space (Ibraeva et al., 2020; Krizek, 2003).

One of the most widely recognized insights in transportation research is that urban form plays a crucial role in shaping mobility behavior (R. Ewing & Cervero, 2017; Næss, 2012). Studies have repeatedly shown that higher density, a diverse land-use mix, and pedestrian-oriented street designs are associated with lower car dependency, more active travel, and increased transit ridership (Cervero, 2001; Frank & Pivo, 1994; Haider & El-Geneidy, 2021). Density, for instance, can reduce the average distance between origins and destinations, making walking or cycling more feasible for everyday trips (Cervero, 2001; Shah et al., 2021). Similarly, a well-balanced mix of land uses enhances accessibility, making it easier for people to access daily needs, often without needing a private vehicle (Cervero, 2001; Cervero & Kockelman, 1997). However, these relationships are not linear, as they involve intricate feedback loops wherein parking availability, perceived safety, and infrastructure quality all shape individuals' mode choices (Frank & Pivo, 1994; Suzuki et al., 2013). Understanding how these variables intersect, and how policy interventions like parking regulations or transit fare changes can shift travel behavior, is crucial for sustainable urban mobility (Ercan, 2016; Frank & Pivo, 1994).

SDM offers a valuable framework for analyzing the dynamic and interrelated components of urban transportation systems, especially where feedback loops play a decisive role in shaping long-term outcomes (Shepherd, 2014; Stroh, 2015). Originating from systems theory, SDM uses stocks, flows, and causal loop diagrams to represent how changes in one part of a system affects other interconnected variables over time (Forrester, 1971). In transportation research, SDM has been employed to explore phenomena such as congestion growth, mode-shift processes, and transit funding (Ercan, 2016; Fontoura et al., 2022; Shepherd, 2014). By capturing these cyclical interactions, SDM facilitates scenario testing, enabling researchers to forecast how specific interventions, like increasing road capacity or investing in public transit, could unfold over decades (Han et al., 2009; Xu, 2012). Despite its strengths, traditional SDM commonly lacks spatial resolution, treating location-specific factors (e.g., proximity to transit stations, land-use configuration) as uniform or aggregated (Guan et al., 2011; Krizek, 2003). This gap suggests the potential for enriching SDM by incorporating geographic data that reflect the differing spatial realities within and between urban regions (Krizek, 2003).

Geographic Information Systems (GIS) have become essential for understanding and managing the spatial complexities of urban areas, particularly in the realm of transportation (Guan et al., 2011). By offering georeferenced data on road networks, land-use patterns, and proximity to amenities, GIS tools reveal how small variations in location can substantially influence travel choices (Han et al., 2009; Liu & Zhu, 2004). For example, a neighborhood's walkability score or the percentage of residents within a given distance of a transit station can be accurately quantified through GIS-based spatial analysis (Carr et al., 2010). Studies in this domain highlight how seemingly modest geographic shifts (such as an additional two or three blocks from a rail stop) can dramatically reduce the likelihood of public transit use (Chatman, 2013). Moreover, GIS approaches have been used to identify "transit deserts," areas where residents lack practical access to frequent or reliable public transportation, and to propose targeted interventions, including new bus routes or bicycle-sharing stations (Liu & Zhu, 2004; Mavoa et al., 2012). While these spatially explicit methods provide valuable policy insights, they often act as static snapshots, identifying where resources are needed but failing to capture the evolving feedback loops, such as how transit improvements might gradually reshape land use and travel behavior over time. (Han et al., 2009; Xu, 2012). This gap underscores the potential synergy between GIS-based metrics of accessibility and land use, and the more dynamic feedback-oriented analyses facilitated by system dynamics modeling (Guan et al., 2011; C. He et al., 2005).

2.1. Integration of System Dynamics and GIS in Urban Sustainability Assessment

Recent advancements in urban sustainability assessment emphasize the need for integrated modeling approaches that capture both temporal dynamics and spatial variations. SDM and GIS have emerged as powerful tools to achieve this integration, allowing researchers to explore complex feedback mechanisms and spatial interactions in urban systems.

Pokharel et al. (2023) employed a two-stage SD modeling approach to investigate car dependency and sustainable mobility policies. Their work highlights the importance of understanding feedback loops and leveraging path dependencies to shift urban transport systems towards sustainability. This approach aligns with the current study's objective of exploring the dynamic interactions between urban form, travel behavior, and sustainability indicators, particularly in brownfield redevelopment projects (Pokharel et al., 2023).

Z. Xu & Coors (2012) proposed a GISSD[1] system that integrates SD modeling, GIS spatial analysis, and 3D visualization for urban sustainability assessment. Their study demonstrates how spatial metrics, dynamic simulations, and visualizations can provide a holistic view of urban systems. This integrated framework directly informs the present study's methodology, which utilizes SD modeling to capture temporal dynamics and GIS tools to quantify spatial variations in urban form and accessibility (Xu, 2012).

Additionally, the work by AlKhereibi et al. (2022) highlights the significance of feedback loops between land-use policies and travel behavior, influencing sustainability outcomes. Their findings underscore the necessity of system-level thinking and dynamic modeling to capture the interdependencies among urban form, policy interventions, and travel patterns. These insights are particularly relevant to the present study's focus on TOD principles and proximity planning (AlKhereibi et al., 2022).

Collectively, these studies provide a solid theoretical foundation for integrating SD and GIS in urban sustainability assessment, validating the current study's methodological framework. They highlight the value of feedback loops, dynamic causal relationships, and spatial-temporal analysis, supporting the development of policy interventions for sus-tainable urban mobility and development. Table 1 presents a comprehensive compilation of indicators derived from the literature, categorized across key dimensions of sustainable urban development, transportation systems, and mobility patterns. By synthesizing data from multiple studies, this table establishes a foundation for assessing the interactions between urban form, travel behavior, and sustainability outcomes, guiding the develop-ment of the proposed SDGIS framework.

[1] Geographical Information System System Dynamics

Table 1 - Table of indicators extracted from the literature. An "X" indicates that the respective study included or discussed the corresponding indicator.

Category	Indicators	References																					
		Robillard et al. (2024)	Zhu et al. (2023)	Dorosan et al. (2024)	Monkkonen et al. (2024)	Haseli et al. (2024)	Elmarakby & Elkadi (2024)	Liao & Scheuer (2022)	Yang (2023)	Berrill et al. (2024)	Nachtigall et al. (2025)	Huang et al. (2024)	Zeng et al. (2024)	Pekdemir et al. (2024)	Olsen et al. (2024)	Fan et al. (2024)	Heroy et al. (2023)	Jama et al. (2025)	Loh et al. (2024)	Nenseth & Røe (2024)	Rabiei et al. (2022)	Sun et al. (2024)	Zhu et al. (2022)
Built Environment	Density	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Mixed land uses	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Design	X	X	X			X				X		X		X	X	X			X		X	
	Accessibility	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Proximity	X	X	X				X		X			X	X	X	X	X	X	X	X	X	X	X
	Walkability	X	X		X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	
	Bikeability	X												X					X		X	X	X
	Block size		X				X						X		X			X			X		
	Green space/public space ratio	X	X			X	X	X	X			X	X	X	X						X		
Transportation	Transportation network	X	X		X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	
	Distance to transit	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	
	Public transit accessibility (travel time to key destinations)	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
	Frequency and reliability of transit services	X	X		X	X		X	X	X	X		X		X					X		X	
	Number of transit stations/stops nearby	X	X		X			X	X	X	X		X	X	X	X	X			X	X	X	
	Ridership levels	X	X		X				X	X	X			X							X	X	X

Category	Indicators	Robillard et al. (2024)	Zhu et al. (2023)	Dorosan et al. (2024)	Monkkonen et al. (2024)	Haseli et al. (2024)	Elmarakby & Elkadi (2024)	Liao & Scheuer (2022)	Yang (2023)	Berrill et al. (2024)	Nachtigall et al. (2025)	Huang et al. (2024)	Zeng et al. (2024)	Pekdemir et al. (2024)	Olsen et al. (2024)	Fan et al. (2024)	Heroy et al. (2023)	Jama et al. (2025)	Loh et al. (2024)	Nenseth & Røe (2024)	Rabiei et al. (2022)	Sun et al. (2024)	Zhu et al. (2022)
Transportation	Parking facilities and demand management	X	X		X	X			X		X			X		X						X	
	Walking infrastructure (walking routes)	X	X					X	X		X		X	X	X		X		X	X	X	X	
	Cycling infrastructure (bike lanes, bike-sharing systems)	X	X			X	X	X	X		X			X	X		X		X	X	X	X	
	Traffic congestion and road safety	X	X	X	X	X	X	X	X			X	X		X	X	X		X	X		X	
Socio-economic	Age distribution		X	X											X		X		X				
	Ethnicity and cultural diversity				X												X		X				
	Vehicle ownership rates	X	X	X		X				X						X	X					X	
	Education level							X		X													
	Household income and affordability	X	X	X	X	X		X	X	X		X	X		X	X	X						
	Employment accessibility		X		X	X			X			X	X	X	X	X	X	X			X	X	X
	Social equity in transport services		X												X		X						

3. Methodological Framework

Understanding the complexities of urban systems and their sustainability requires a robust and integrative approach. This section presents the methodological framework developed in this study, combining SD modeling with GIS analysis. The framework is designed to capture the temporal dynamics and spatial characteristics of urban form, travel behavior, and sustainability outcomes. By integrating these two complementary methods, the framework provides a powerful tool for exploring causal relationships, assessing policy impacts, and informing urban planning decisions.

3.1. Research Question & Objectives

This study seeks to answer the following research questions:

How can an integrated System Dynamics (SD) and Geographic Information Systems (GIS) framework be utilized to assess the sustainability of urban transportation systems, particularly in brownfield redevelopment projects?

To address this question, the study pursues the following objectives:

1. Develop a conceptual SD-GIS framework that combines dynamic feedback modeling with spatial analysis to evaluate the impacts of urban form, transit accessibility, and parking policies on travel behavior and sustainability outcomes.
2. Identify key sustainability indicators relevant to urban mobility by extracting and re-fining variables from literature and case studies
3. Explore the interactions between land use, parking regulations, and transit investments in shaping travel behavior and greenhouse gas (GHG) emissions, using a qualitative system modeling approach.
4. Apply the proposed framework to two case studies (Bridge-Bonaventure and Lachine-Est) to conceptually assess how variations in density, transit accessibility, and parking policies influence mode share and vehicle ownership trends.
5. Generate qualitative policy recommendations based on the framework's insights, providing guidance for integrating TOD principles, parking management, and active transportation infrastructure in sustainable urban development.

While this study does not present a fully quantified simulation, it establishes a methodological foundation for future research by integrating spatial dynamics with system feedback analysis. The insights generated serve as an initial step toward a more comprehensive quantitative evaluation in future applications of the SD-GIS framework.

3.2. Design Thinking: Applying Divergent-Convergent

This study employs an iterative Diverge-Converge approach from Design Thinking (Cucuzzella, 2022) to refine research questions and model components. Initially, a broad literature review on sustainability assessment in urban development and transportation helped identify a wide range of potential indicators (divergence). These indicators were then filtered and structured into Causal Loop Diagrams (CLD), capturing key feedback mechanisms (convergence).

Through multiple refinement cycles, these indicators were further adjusted to fit the Stock and Flow Diagrams (SFD), ensuring a well-calibrated SD–GIS framework. This iterative process allowed for a continuous evolution of the model, integrating both spatial and dynamic aspects of urban sustainability.

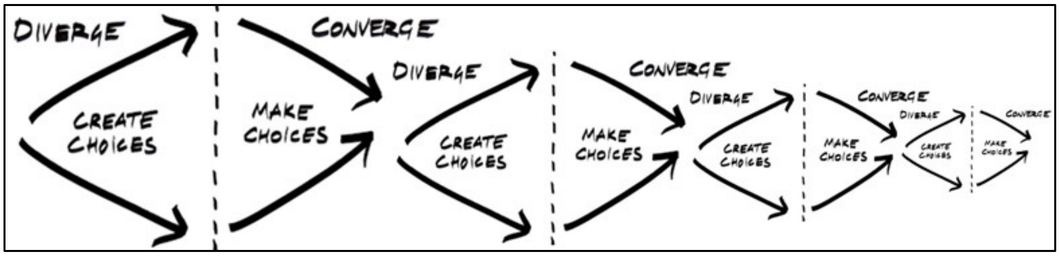

Figure 1. The iterative Diverge-Converge process in research, inspired by Design Thinking, illustrating continuous refinement of questions and ideas until a well-defined framework is achieved (Cucuzzella, 2022).

3.3. Modeling

The overall workflow of the methodological framework is depicted Figure 2. It outlines the sequential steps, starting from the identification of gaps in existing literature, followed by the selection of key variables, development of causal loop diagrams (CLDs), construction of stock and flow diagrams (SFDs), and analysis of causal relationships. The integration of SD and GIS tools forms the core of this methodology, allowing for a detailed and multi-dimensional exploration of sustainability in urban systems.

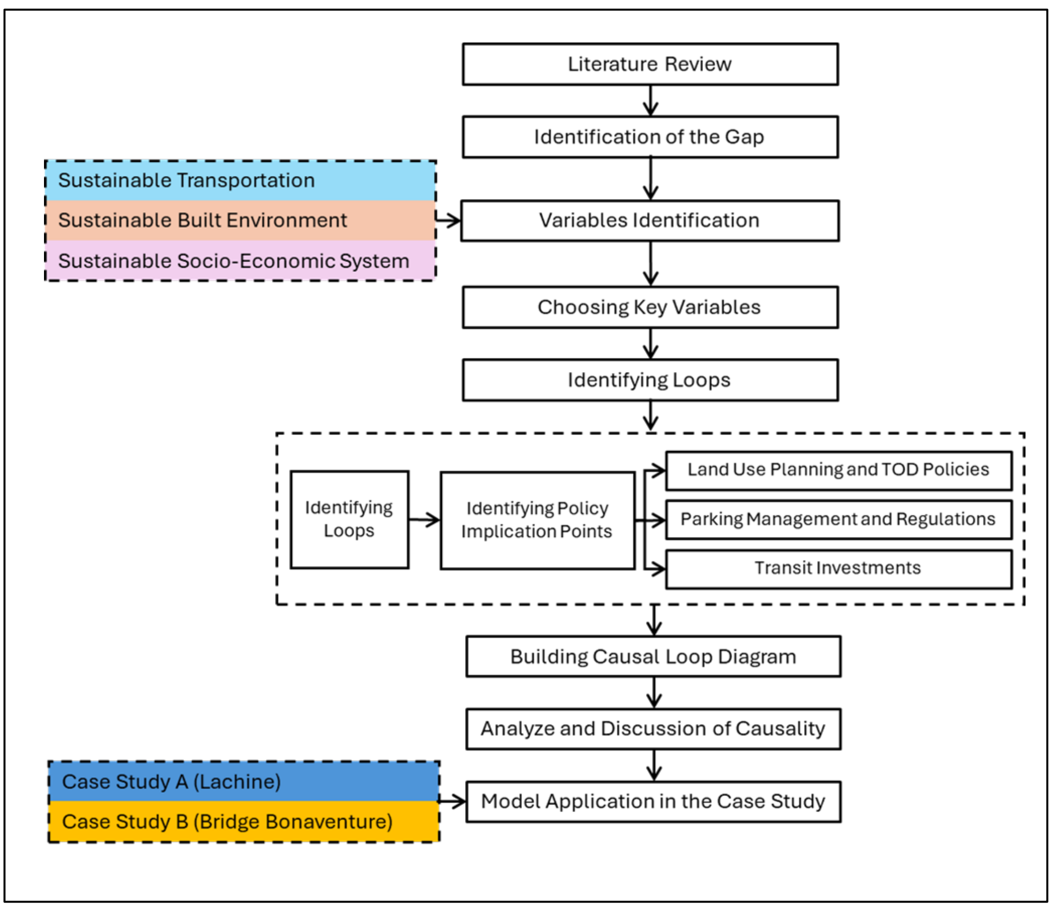

Figure 2. Methodological workflow showcasing the steps from literature review and gap identification to model application and case study.

The proposed methodological framework integrates SD modeling and GIS-based spatial analysis to assess urban transportation sustainability dynamically and spatially. This framework addresses gaps identified in existing sustainability assessment studies by:

1. Capturing the temporal and feedback relationships among urban form, travel behavior, and sustainability indicators (e.g., greenhouse gas emissions, active transportation share).
2. Quantifying spatial metrics, such as accessibility and proximity, to incorporate location-specific dynamics and spatial variations.
3. Providing a tool for policymakers to evaluate the implications of urban development strategies, such as TOD and investments in active transportation infrastructure.

SD modeling captures dynamic causal relationships within urban systems, such as feedback loops between travel behavior, urban density, and sustainability metrics. It enables simulations to explore how changes in urban form and transit accessibility influence travel patterns and sustainability outcomes over time.

3.4. Integrating System Dynamics and GIS

GIS tools complement SD modeling by quantifying spatial variations in urban form, proximity to transportation infrastructure, and accessibility. These spatial insights enhance the framework by providing proximity-based measures (e.g., distance to transit hubs, walkability) and visualizing the spatial distribution of sustainability indicators.

Together, this framework provides a comprehensive approach to understanding the temporal and spatial dynamics of urban transportation systems, offering actionable insights for designing sustainable and transit-oriented urban environments.

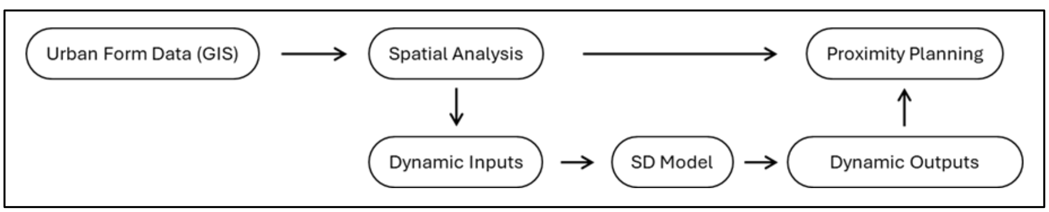

Figure 3. Conceptual workflow of the proposed methodological framework integrating Geographic Information Systems (GIS) and System Dynamics (SD) modeling.

Figure 3 illustrates the conceptual workflow of the proposed methodological framework, which integrates Geographic Information Systems (GIS) and System Dynamics (SD) modeling to assess urban sustainability. This workflow highlights the sequential and interconnected processes involved in analyzing urban form, travel behavior, and sustainability indicators.

- Urban Form Data (GIS): The framework begins with the collection and processing of spatial data related to urban form metrics such as land-use mix, density, street connectivity, and proximity to transportation infrastructure. These datasets are typically obtained from GIS sources like census data, OpenStreetMap, or municipal planning databases.
- Spatial Analysis: GIS tools are applied to analyze spatial relationships and generate metrics such as accessibility, proximity, and network connectivity. These spatial insights provide a foundational understanding of how urban form influences transportation dynamics.
- Dynamic Inputs: The spatial metrics derived from the GIS analysis are converted into inputs for the System Dynamics model. These inputs represent critical variables such as transit accessibility,

mode shares, and infrastructure quality, enabling a dynamic exploration of urban transportation systems.

- SD Model: The SD model simulates the causal relationships and feedback loops among urban form, travel behavior, and sustainability indicators. This dynamic analysis captures temporal changes and system interactions over time, offering a comprehensive view of urban sustainability.
- Dynamic Outputs: The SD model generates outputs such as greenhouse gas (GHG) emissions, mode share variations, and changes in travel demand. These outputs reflect the long-term impacts of urban planning policies and interventions.
- Proximity Planning: The final stage involves translating the model outputs into actionable insights for proximity planning. Policymakers and urban planners can use these findings to design and implement strategies that promote sustainable urban environments, such as TOD and investments in active transportation infrastructure development.

4. Model Structure

4.1. Urban Density and TOD Policies

Urban density plays a central role in shaping transportation behavior and sustainability outcomes. Within the designed system, density is embedded in multiple feedback loops that influence transit accessibility, active travel, car dependency, and parking demand. However, the key aspect of density that needs to be emphasized is how implementing TOD policies while modifying urban density can amplify or counteract sustainability efforts. The interactions between urban density and transportation-related variables reveal whether urban development strategies push cities toward or away from sustainable mobility.

4.1.1. The Role of TOD in Urban Density and Sustainable Mobility

TOD policies aim to foster compact, high-density, mixed-use neighborhoods with strong transit accessibility. Increasing density near transit hubs enhances accessibility to essential services, employment centers, and transit stations, reducing the need for private vehicle trips. This improved accessibility encourages a shift toward public transit, cycling, and walking, ultimately lowering car dependency and GHG emissions.

As shown in Figure 4, this transition forms a balancing feedback loop. Reduced car dependency decreases the demand for parking, enabling more space to be allocated to pedestrian-friendly and transit-supportive development. This in turn strengthens the case for further TOD investments, creating a self-sustaining cycle that enhances urban sustainability.

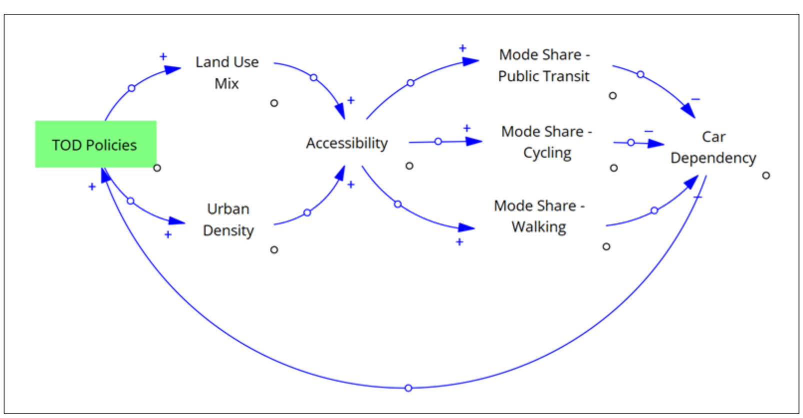

Figure 4. The reinforcing feedback loop of TOD) policies, showing how increasing urban density and land use mixes improve accessibility, promote active and public transportation, and reduce car dependency.

Balancing Loop: *TOD Policies → Higher Urban Density near Transit → Improved Transit Accessibility → Higher Public Transit Ridership & Active Travel → Lower Car Dependency → Reduced Parking Demand → Reinforced TOD Investment*

This loop highlights how TOD interventions enhance the sustainability of urban transportation systems. Higher density fosters better transit access, which leads to increased ridership and reduced reliance on private vehicles. As car dependency declines, parking demand decreases, enabling further pedestrian-oriented, mixed-use development. The strengthened feasibility of TOD policies supports continued investments in transit and active mobility infrastructure.

Table 2. TOD Policies and Their Influence on Urban Density and Sustainable Mobility.

SN	Variables and Relationship	Causal Mechanism	Supporting Literature Examples
1	Density near transit hubs → (+) Accessibility	Increasing density near transit hubs enhances accessibility to public transportation.	(Cervero & Kockelman, 1997; Newman et al., 2016)
2	Accessibility → (+) Public transit ridership	Improved transit accessibility encourages more people to use public transit.	(Cervero, 2002; R. Ewing & and Cervero, 2010)
3	More people using transit & active modes → (+) Reduces car dependency	A higher share of transit and active modes reduces reliance on private vehicles.	(Miller et al., 2016; Zahabi et al., 2012)
4	More people using transit & active modes → (−) Car dependency	Reduced reliance on private vehicles leads to a decline in car ownership.	(Handy et al., 2005; Van Acker & Witlox, 2010)
5	Lower car dependency → (−) Parking Demand	Lower car dependency decreases the demand for parking spaces.	(Albalate & Gragera, 2020; Guo, 2013)
6	Lower parking demand → (+) Urban Development near transit	With lower parking demand, more space is available for compact, mixed-use development.	(Cervero & Kockelman, 1997)
7	More high-density development → (+) Justifies further TOD investment	Increased high-density development supports further investment in TOD policies.	(Chatman, 2013; Langlois et al., 2015)

4.1.2. Policy Implication: TOD in the Three Ds (Density, Diversity, and Design)

While implementing TOD policies, urban planners must carefully consider the 3D framework-Density, Diversity, and Design-to ensure that urban density is not only increased but also well-integrated with transit, land use, and active mobility infrastructure. Density alone is insufficient; without diverse land-use planning and a well-designed pedestrian environment, the full potential of TOD in reducing car dependency and improving sustainability may not be realized.

4.2. Parking Policies and Car Dependency

4.2.1. The Role of Parking Policies in Sustainable Urban Development

Parking policies are a fundamental aspect of urban planning, directly influencing car ownership, travel behavior, and the overall sustainability of urban developments. In many cities, excessive parking supply has reinforced private car dependency, contributing to increased congestion, reduced public transit ridership, and a car-oriented urban structure. However, well-designed parking policies, including parking regulations, pricing strategies, and TOD initiatives, can serve as regulatory tools to shift travel behavior toward more sustainable alternatives such as public transit, walking, and cycling.

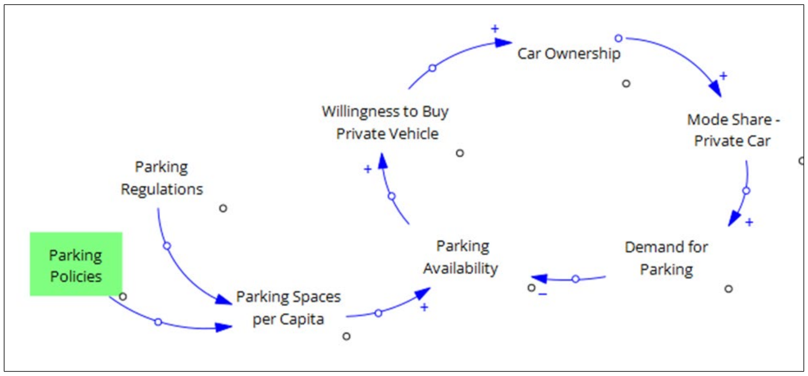

Figure 6. Balancing loop for the Role of Parking Policies in Car Dependency and Urban Mobility.

Balancing Loop: *More Parking Spaces per Capita → Higher Parking Availability → Increased Willingness to Own a Car → Higher Car Ownership → Increased Parking Demand → Reinforced Car Dependency*

Table 3. Parking Policies, Car Dependency, and Urban Mobility.

SN	Variables and Relationship	Causal Mechanism	Supporting Literature Examples
1	Parking spaces per capita → (+) Parking availability	More parking spaces increase overall parking supply.	(Florian & Los, 1980; Shoup, 2006)
2	Parking availability → (+) Willingness to buy a private vehicle	Easier parking access encourages car ownership.	(Guo, 2013; Yan et al., 2019)
3	Willingness to buy a private vehicle → (+) Car ownership	Higher willingness to buy a car leads to increased vehicle ownership.	(S. Y. He & Thøgersen, 2017; Verma et al., 2016)
4	Car ownership → (+) Mode share for private cars	Increased vehicle ownership raises the percentage of car-based travel.	(Anowar et al., 2016; Ding et al., 2017; Miller et al., 2016)
5	Mode share for private cars → (+) Demand for parking	A higher proportion of trips made by car increases parking demand.	(Christiansen et al., 2017; Parmar et al., 2020)
6	Demand for parking → (+) Parking availability	A higher parking demand leads to a push for more parking spaces.	(Brown et al., 2001; Litman, 2005; Van Acker & Witlox, 2010)

This loop highlights a key issue in urban planning: providing more parking does not necessarily satisfy parking demand in the long run. Instead, an increase in parking spaces per capita makes private car ownership more convenient and attractive, leading to higher vehicle dependency. As more people own cars, the demand for additional parking increases, creating a cycle that prioritizes private vehicle use over sustainable transportation.

4.2.2. Breaking the Cycle: Parking Policies as a Regulatory Tool

To counteract the reinforcing effect of excessive parking supply on car dependency, urban planners can implement the following regulatory strategies:

1. Reducing Parking Minimums in TOD Zones: Limiting mandatory parking requirements in high-density areas promotes TODs that prioritize sustainable mobility.
2. Dynamic Parking Pricing: Adjusting parking fees based on demand discourages unnecessary car trips and increases the attractiveness of public transit.
3. Caps on Parking Spaces Per Capita in New Developments: Placing restrictions on the number of parking spaces allocated per resident prevents an oversupply that reinforces vehicle dependency.

4. Investment in Public Transit and Active Transportation: Expanding transit services and enhancing pedestrian and cycling infrastructure ensures that parking restrictions do not compromise accessibility but rather encourage multimodal transportation.

4.2.3. Policy Interference: Parking Policies

Parking policies, parking regulations, and parking costs interact within this balancing loop, affecting the long-term sustainability of urban mobility. The most critical insight from this loop is that simply increasing parking supply does not solve parking shortages, rather, it incentivizes further car ownership, increasing demand for parking and undermining sustainability efforts. By strategically integrating parking policies with TOD principles and active transportation investments, urban developments can shift away from car dependency and toward a more balanced and sustainable mobility network.

4.3. Investment in Active Transportation – Walking and Cycling

4.3.1. The Role of Active Transportation in Sustainable Urban Mobility

Active transportation, including walking and cycling, is a fundamental component of sustainable urban development. Investments in pedestrian infrastructure, bike lanes, and bike-sharing networks create an environment that supports non-motorized travel, reducing car dependency, congestion, and greenhouse gas (GHG) emissions. Without adequate infrastructure, however, walking and cycling remain unsafe, disconnected, and inconvenient, reinforcing car reliance and discouraging active travel. Breaking this cycle requires strategic investments in active transportation infrastructure, generating a balancing loop that encourages sustainable mobility.

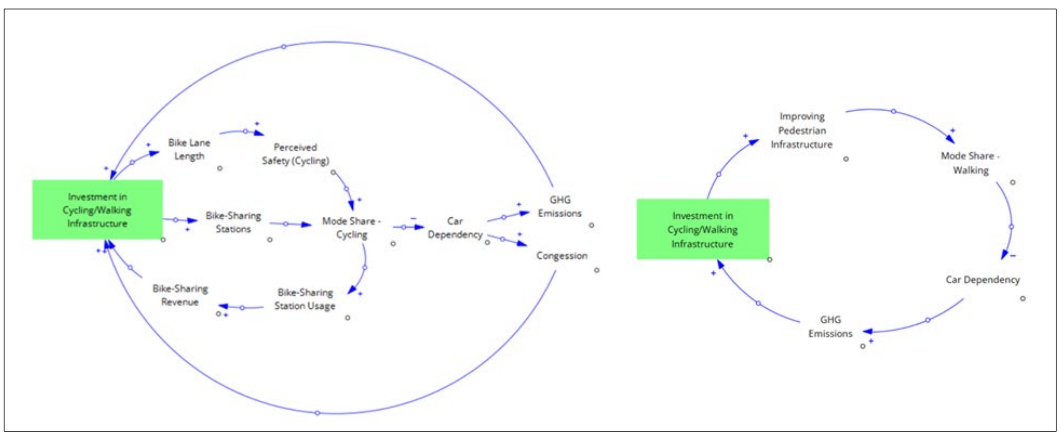

Figure 7. The Reinforcing Effects of Investment in Active Transportation on Cycling and Walking Mode Share.

Balancing Loop: *Increased Investment in Cycling and Walking Infrastructure → Expanded Bike Lanes, Bike-Sharing Stations & Pedestrian Facilities → Improved Perceived Safety and Connectivity → Higher Mode Share for Walking & Cycling → Reduced Car Dependency → Lower Congestion and GHG Emissions → Lower Investment in Active Transportation*

Table 4. Investments in Active Transportation, Mode Share, and Sustainability.

SN	Variables and Relationship	Causal Mechanism	Supporting Literature Examples
1	Investment in cycling/walking infrastructure → (+) Improved pedestrian & cycling infrastructure	Expanding bike lanes and pedestrian pathways enhances connectivity and safety.	(Pucher et al., 2010; Sloman et al., 2009)

2	Improved pedestrian & cycling infrastructure → (+) Perceived safety for walking & cycling	Dedicated infrastructure reduces risks, making active travel more attractive.	(Hull & and O'Holleran, 2014; Southworth, 2005)
3	Perceived safety for walking & cycling → (+) Mode share for walking & cycling	Increased safety encourages greater adoption of non-motorized modes.	(Lawson et al., 2013; Saelens & Handy, 2008)
4	Higher walking & cycling mode share → (-) Car dependency	Increased active travel reduces reliance on private vehicles.	(Buehler et al., 2017; Newman et al., 2016)
5	Reduced car dependency → (-) GHG emissions & congestion	Fewer car trips result in lower emissions and less road congestion.	(Laakso, 2017; Mun Ng et al., 2024; Neves & Brand, 2019)
6	Lower emissions & congestion → (+) Further lower investment needed in active transportation	Positive environmental outcomes justify that sufficient funding for sustainable mobility has been places and lower funding is needed in the future.	(R. H. Ewing, 2008; Langlois et al., 2015)

This loop demonstrates how investments in active transportation lead to widespread behavioral shifts, reducing car dependency and strengthening the overall sustainability of urban mobility until it.

4.3.2. Breaking the Cycle: Strategies for Strengthening Active Transportation

To increase the shift toward active mobility, the following policy interventions are recommended:

1. Expanding Protected Bike Lanes & Sidewalks: Ensuring a safe, direct, and connected network for cyclists and pedestrians.
2. Enhancing Bike-Sharing Networks: Increasing the availability of shared bikes to improve first-mile/last-mile connectivity.
3. Improving Pedestrian Infrastructure: Prioritizing investments in sidewalks, crossings, and traffic-calming measures to enhance walkability.
4. Integrating Active Transportation with Public Transit: Creating seamless connections between cycling, walking, and transit to reduce car dependency.
5. Long-Term Funding & Policy Support for Active Modes: Allocating consistent financial resources to ensure infrastructure maintenance and expansion.

By strategically integrating active transportation investments with TOD and urban land use planning, cities can create human-scaled, walkable environments that minimize reliance on private vehicles and promote healthier, more sustainable mobility patterns.

4.3.3. Policy Interference: Active Transportation Investments

The reinforcing loop identified in this study emphasizes how investments in cycling and pedestrian infrastructure support long-term behavioral change. However, policy barriers such as car-centric urban planning, lack of dedicated funding, and inadequate integration with land use planning can hinder the effectiveness of active transportation investments. Addressing these barriers requires a coordinated approach that prioritizes sustainable mobility, enhances multimodal accessibility, and ensures that walking and cycling infrastructure is an integral part of urban development.

4.4. Integrating GIS into the System Dynamics Model: The Role of Spatial Analysis in TOD Policies

With the identification of key feedback loops and their implications, the next step is to highlight the role of GIS in refining the spatial precision and policy relevance of the model. GIS serves as a crucial tool for integrating location-based insights into the dynamic relationships of the system, ensuring that TOD policies are effectively implemented.

A fundamental challenge in TOD planning is determining the optimal locations for density concentration to enhance transit accessibility and reduce car dependency. TOD success is inherently location-dependent, requiring spatial analysis to evaluate land-use configurations, accessibility patterns, and travel behavior shifts. By integrating GIS into SDM, this research provides a framework that captures both spatial and temporal dynamics, offering a more comprehensive understanding of urban mobility and sustainability outcomes.

4.4.1. GIS Contributions to System Dynamics Modeling

GIS enhances the methodological framework by addressing the spatial dependencies of TOD policies and their influence on travel behavior. The integration of GIS allows for:

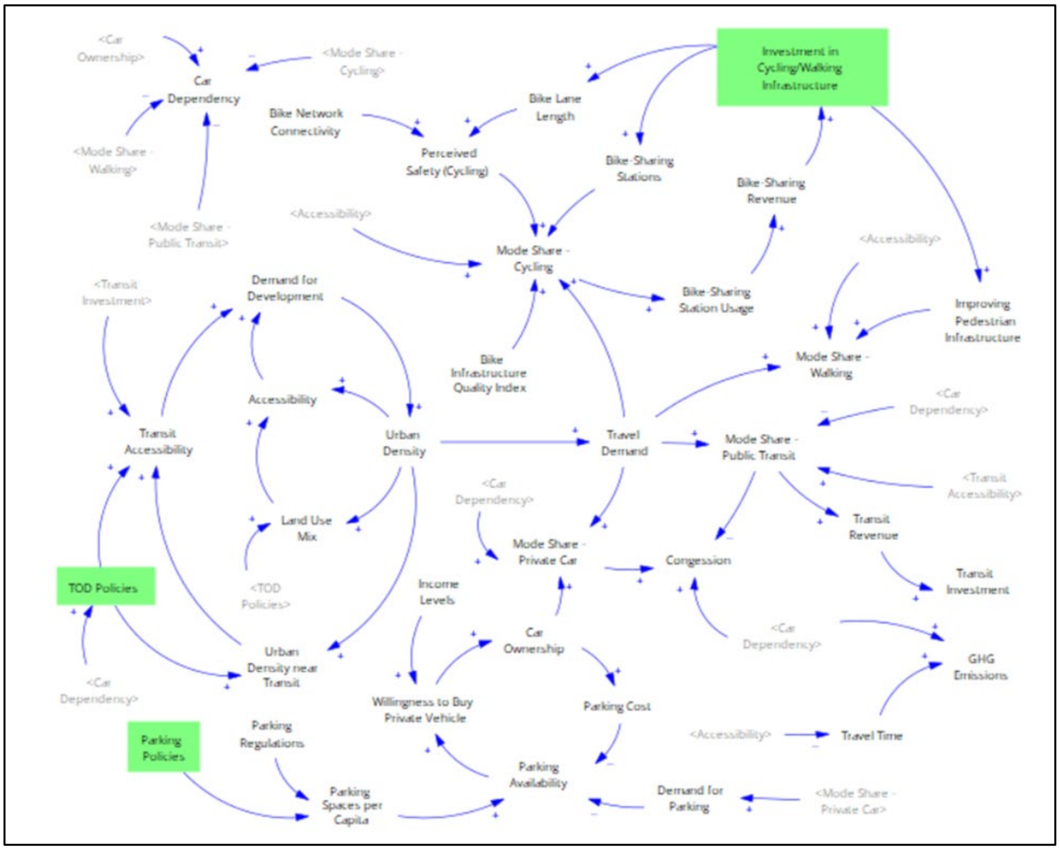

Figure 8. Causal Loop Diagram.

1. Defining and Analyzing TOD Zones involves identifying optimal areas for higher-density development by assessing their proximity to existing and planned transit stations. It also requires evaluating land-use configurations to ensure that mixed-use developments are well-integrated with accessibility and mobility objectives.
2. Measuring Transit Accessibility Impacts includes analyzing how changes in density influence transit accessibility, thereby encouraging a shift toward public transportation. Additionally, GIS-based network analysis is used to measure walking distances to transit stops and assess equitable access to transit services.
3. Assessing Active Transportation Infrastructure entails evaluating walkability and bikeability within TOD zones to improve last-mile connectivity. Furthermore, it involves identifying gaps in pedestrian and cycling infrastructure that could hinder the effectiveness of TOD initiatives.
4. Optimizing Parking Policy Implementation requires conducting spatial analysis of parking distribution to inform strategies for reducing parking supply in TOD zones. It also involves

identifying areas where parking adjustments can help decrease car dependency while maintaining transit accessibility.

5. Scenario-Based Planning for Sustainable Mobility includes simulating how variations in density and land-use configurations influence mode share, vehicle ownership, and GHG emissions. Additionally, it involves testing different TOD and parking policy interventions to determine the most effective strategies for reducing automobile reliance.

4.4.2. Using GIS to Enhance TOD Policy Design

GIS enhances decision-making by spatially defining TOD zones, analyzing accessibility changes, and optimizing density allocations. By integrating GIS into system dynamics modeling, this research presents a comprehensive and scalable approach to evaluating the long-term effects of TOD policies on urban mobility and sustainability.

How GIS Enhances the TOD Feedback Loop: *TOD Policies → GIS-Based TOD Zone Definition → Improved Accessibility to Transit → Reduced Car Dependency → Increased TOD Justification → Further TOD Investments*

By incorporating spatial analysis into the modeling framework, this approach ensures that TOD investments are strategically implemented to maximize sustainability objectives. The integration of GIS enables data-driven decision-making, supporting urban planners and policymakers in identifying the most effective locations for TOD interventions while balancing density, accessibility, and transportation infrastructure.

5. Conclusion

This study presented a conceptual SD–GIS framework as an early step toward building integrated tools for assessing urban transportation sustainability. The framework highlights the need to combine system-level feedbacks with spatial proximity metrics to capture the complex interactions between density, TOD policies, and parking supply. At this stage, the contribution is primarily methodological: it lays the groundwork for subsequent empirical applications. Later research extended this framework to case studies of brownfield redevelopment in Montreal, where the impacts of TOD and parking policies on car dependency and greenhouse gas emissions were evaluated in detail (see Farnood et al., 2025, Smart Cities). By sharing this preliminary version at the System Dynamics Conference, our aim is to engage with the academic community on the value of linking SD and GIS approaches and to invite feedback that informed the refinement of later work.

Note: This conference paper presents the preliminary conceptual framework of our research. The extended version, including case study applications, has since been published as a peer-reviewed journal article (Farnood et al., 2025, Smart Cities).

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