Evaluating the Impact of Removing the Green Line D Branch on Traffic Demand Allocation and Network Performance in Boston

Duy Nguyen
Vishnu Sreekumar

Department of Civil and Environmental Engineering
Northeastern University

CIVE 7381 – Transportation Demand Models

Instructor: Professor Haris Koutsopoulos

December 2025

Contents

Abstract

This study evaluates the impacts of removing the MBTA Green Line D branch on travel behavior and roadway network performance in the Boston metropolitan area. A four-step travel demand modeling framework is applied, incorporating fixed trip generation and distribution, a nested logit mode choice model, and user-equilibrium auto traffic assignment in TransCAD. Two scenarios are analyzed: a base case and a network configuration without the Green Line D branch. Results indicate modest increases in vehicular congestion and a redistribution of home-based work trips between auto and transit modes driven by relative changes in generalized travel cost. The findings highlight the sensitivity of dense urban networks to transit service disruptions and provide insights relevant to transportation system resilience and policy planning.

1 Introduction

1.1 Background and Motivation

The Massachusetts Bay Transportation Authority (MBTA) Green Line is a critical component of Boston's regional transit network, providing high-capacity rail service between the western suburbs and major employment and educational centers within the city. Among its branches, the D branch serves dense residential areas and functions as a key alternative to parallel arterial roadways such as Commonwealth Avenue, Beacon Street, and Route 9. As a result, disruptions to the D branch have the potential to affect not only transit riders but also overall traffic conditions across the surrounding roadway network.

Recent service suspensions and maintenance-related closures of the Green Line D branch provide a real-world context for examining how urban travel systems respond to the loss of a major rail service. Understanding these responses is important for transportation planning, particularly in cities with constrained roadway capacity and high reliance on public transit.

1.2 Problem Statement

The removal of a high-capacity rail transit service alters generalized travel costs across modes, potentially changing travelers' mode choices and affecting roadway congestion. However, the magnitude and spatial distribution of these effects are not always intuitive. Increased roadway congestion may also reduce the attractiveness of auto travel, leading to complex behavioral responses within the transportation system.

This study evaluates how removal of the Green Line D branch affects the allocation of home-based work (HBW) trips between auto and transit modes, as well as resulting impacts on roadway network performance. The analysis focuses on redistribution of existing travel demand rather than changes in total trip generation.

1.3 Study Objectives

The primary objectives of this study are to:

- assess changes in vehicular traffic volumes, congestion levels, and travel times resulting from removal of the Green Line D branch;
- examine how HBW mode choice reallocates between auto and transit in response to altered network conditions;
- compare base case conditions with a no–D branch scenario; and

- provide insights into implications for transit resilience and policy planning.

2 Literature Review

This study draws upon three primary strands of transportation research: (1) the impacts of transit service disruptions on travel behavior, (2) mode choice modeling using discrete choice theory, and (3) roadway network performance modeling under congestion. Together, these bodies of literature provide the theoretical foundation for analyzing how the removal of a major rail transit service affects mode allocation and traffic conditions.

2.1 Transit Service Disruptions and Travel Behavior

A substantial body of research has examined how travelers respond to transit service disruptions, including rail line closures, strikes, and planned maintenance shutdowns. Early studies demonstrate that transit disruptions often lead to increased auto usage and roadway congestion, particularly in dense urban areas where transit plays a central role in daily mobility [2]. However, the magnitude of these effects varies widely depending on network redundancy, availability of substitute modes, and traveler adaptability.

More recent work emphasizes that traveler responses to disruptions are not limited to direct shifts from transit to auto. Instead, travelers may adjust departure times, reroute trips, switch to alternative transit services, or change activity patterns altogether [1]. In networks with multiple transit options, the loss of a single rail service can result in redistribution of trips among remaining transit modes rather than a complete abandonment of transit. This highlights the importance of modeling transit disruptions within a system-wide framework that accounts for relative generalized travel costs across all available modes.

Studies of rail shutdowns in metropolitan areas such as New York, London, and Paris further indicate that congestion impacts are often spatially concentrated along corridors parallel to the disrupted service [3]. These findings suggest that evaluating both mode choice and roadway network performance is necessary to capture the full effects of transit service removal.

2.2 Discrete Choice Models and Mode Selection

Mode choice modeling in transportation planning is grounded in random utility theory, which assumes that travelers select the mode that maximizes their individual utility subject to constraints [4]. Multinomial logit models have long been used to represent mode choice behavior due to their computational simplicity and clear behavioral interpretation. However, the assumption of independence of irrelevant alternatives (IIA) can limit their applicability when alternatives share unobserved attributes.

Nested logit models relax the IIA assumption by allowing correlation among alternatives within nests, making them particularly suitable for modeling choices between auto and multiple transit options [5]. Empirical studies consistently find that travel time, monetary cost, parking cost, and socioeconomic characteristics such as income are among the most influential determinants of mode choice. Parking cost, in particular, has been shown to be a strong deterrent to auto use in central urban areas, often exerting a larger marginal effect than travel time alone [6].

In the context of transit disruptions, discrete choice models have been used to capture how changes in generalized travel cost influence mode allocation. Importantly, increases in auto congestion can reduce the relative attractiveness of driving, potentially offsetting some of the mode shifts away from transit. As a result, changes in mode share following a transit disruption are not always monotonic or intuitive, underscoring the value of utility-based modeling approaches.

2.3 Traffic Assignment and Network Performance Modeling

Roadway network performance under congestion is commonly modeled using traffic assignment techniques based on Wardrop's first principle, which states that no traveler can unilaterally reduce travel time by switching routes at equilibrium [7]. User equilibrium (UE) assignment remains the standard approach in regional travel demand models and is widely implemented in planning software such as TransCAD.

Congestion effects are typically represented through volume–delay functions (VDFs), with the Bureau of Public Roads (BPR) function being the most commonly used. The nonlinear relationship between traffic volume and travel time implied by the BPR function reflects empirical observations that congestion increases rapidly as demand approaches capacity. Consequently, relatively small increases in traffic demand can result in disproportionately large increases in delay on critical links.

Previous research demonstrates that transit service reductions can trigger such nonlinear congestion responses on parallel roadways, even when overall increases in auto demand are modest [8]. This underscores the importance of evaluating link-level performance measures such as volume-to-capacity ratios, delay, and travel time when assessing the impacts of transit disruptions.

2.4 Synthesis and Relevance to This Study

The literature collectively suggests that the impacts of removing a major rail transit service extend beyond simple shifts from transit to auto. Instead, the effects manifest through complex interactions between mode choice behavior and network congestion dynamics. Discrete choice models provide a behavioral framework for capturing relative changes in mode attractiveness, while traffic assignment models translate these behavioral responses into measurable impacts on roadway performance.

Building on this foundation, the present study applies a four-step travel demand model with a nested logit mode choice formulation and user equilibrium traffic assignment to evaluate the impacts of removing the MBTA Green Line D branch. By focusing on changes in mode allocation and network performance rather than total trip generation, the analysis aligns with established theoretical and empirical insights from the transportation literature.

3 Data and Study Area

3.1 Study Area

The study area covers the Boston metropolitan region as defined by the Boston Metropolitan Planning Organization (MPO). This region includes the City of Boston and surrounding municipalities that are connected through a dense multimodal transportation network consisting of highways, arterial roadways, local streets, and an extensive public transit system operated by the Massachusetts Bay Transportation Authority (MBTA). The Green Line D branch serves as a key radial transit corridor within this network, linking western suburban areas to major employment, educational, and activity centers in downtown Boston and Cambridge.

The spatial resolution of the analysis is based on Transportation Analysis Zones (TAZs) defined by the Boston MPO. These zones provide a standardized geographic framework for representing travel demand, land use characteristics, and network connectivity in regional travel demand modeling. Roadway performance is evaluated at the link level, allowing congestion effects to be examined along corridors parallel to the Green Line D branch as well as across the broader regional network.

3.2 Data Sources

The datasets used in this study were provided by Muhammad, a postdoctoral researcher working with Professor Haris Koutsopoulos, and are consistent with data commonly employed in regional transportation planning and research. The data integrate public transit information with roadway network and zonal attributes for the Boston metropolitan area.

Transit service characteristics were derived from General Transit Feed Specification (GTFS) data for the MBTA system. The GTFS dataset includes detailed information on transit routes, stops, schedules, and travel times, enabling the representation of rail and bus services within the mode choice model. In particular, the GTFS data were used to construct transit travel time components and service attributes associated with the Green Line network.

Roadway network data were obtained from the Boston MPO and include detailed link and node attributes such as functional classification, number of lanes, free flow speed, capacity, and directionality. These data form the basis for the auto network used in the traffic assignment procedure. In addition, zonal attributes and interzonal impedance measures provided by the MPO were used to define trip origins and destinations and to support mode choice modeling.

3.3 Data Processing and Preparation

Prior to model implementation, the datasets were processed to ensure consistency across spatial and modal components. GTFS-based transit travel times were aggregated to the TAZ level to generate interzonal transit skim matrices used in the mode choice model. Roadway network links and nodes were checked for connectivity, directionality, and attribute completeness before being imported into TransCAD for traffic assignment.

Transportation Analysis Zones were linked to the roadway and transit networks to enable the integration of demand and supply components within the four-step modeling framework. All datasets were reviewed for missing values and outliers, and necessary adjustments were made to ensure that the base case network accurately represents typical operating conditions in the Boston region.

Together, these datasets provide a comprehensive representation of both transit and roadway systems, allowing for the evaluation of changes in mode choice and network performance resulting from the removal of the Green Line D branch.

4 Methodology

This study applies a four-step travel demand modeling framework to evaluate the impacts of removing the MBTA Green Line D branch. Figure 1 summarizes the modeling workflow.

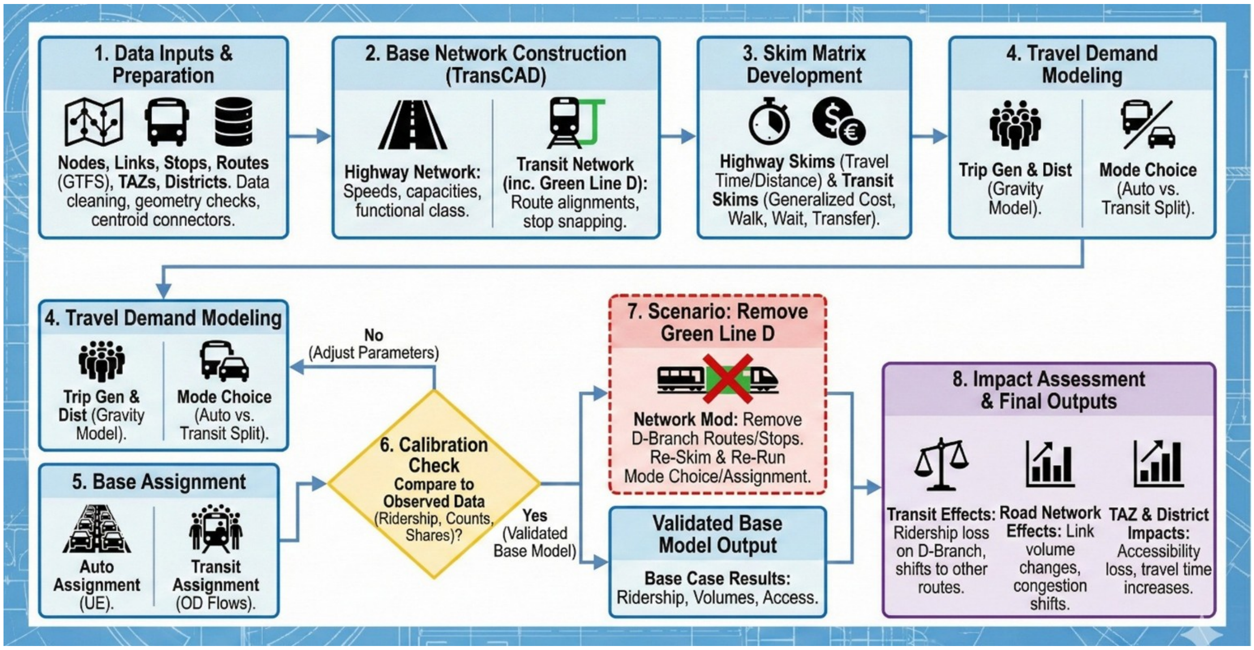

Figure 1: Overview of the travel demand modeling framework and scenario analysis applied in this study.

4.1 Data Inputs and Network Preparation

The modeling process begins with the preparation of roadway and transit network datasets, including nodes, links, routes, and Transportation Analysis Zones (TAZs). Transit service attributes were derived from General Transit Feed Specification (GTFS) data for the MBTA system, while roadway network attributes, such as capacity, free-flow speed, number of lanes, and functional classification, were obtained from Boston Metropolitan Planning Organization (MPO) datasets. Centroid connectors were established to link TAZs to the roadway and transit networks, and geometric and attribute consistency checks were performed to ensure network integrity.

4.2 Base Network Construction

Separate but integrated roadway and transit networks were constructed in TransCAD. The roadway network represents auto travel and includes directional links, capacity constraints, and congestion-sensitive travel times. The transit network includes rail and bus services, with explicit representation of the Green Line D branch in the base case. Stop locations, route alignments, and service attributes were mapped to the network to enable multimodal analysis.

4.3 Skim Matrix Development

Interzonal skim matrices were developed for both auto and transit modes. Auto skims include travel time and distance derived from free-flow conditions, while transit skims incorporate in-vehicle travel time, walking time, waiting time, transfer penalties, and monetary cost. These skim matrices represent generalized travel cost components and serve as inputs to the mode choice model. Skims were generated consistently across scenarios to ensure comparability of results.

4.4 Travel Demand Modeling

Trip generation and trip distribution were held constant across scenarios to isolate the effects of network changes on mode choice and traffic performance. Trip distribution was based on a gravity model formulation, producing fixed origin–destination (OD) trip tables for home-based work (HBW) trips.

Mode choice was modeled using a disaggregate nested logit formulation. The model includes auto and transit alternatives, with utility functions specified as linear combinations of travel time, monetary cost, parking cost, and household income. Travel time and fare coefficients were constrained to be consistent across modes, while parking cost and income effects were applied to the auto alternative only. Mode choice outputs consist of OD-specific probabilities, which were applied to the fixed OD matrices to allocate trips between auto and transit.

4.5 Traffic Assignment

Auto trips resulting from the mode choice step were loaded onto the roadway network using a user-equilibrium (UE) traffic assignment. Congestion effects were represented using volume–delay functions, capturing the nonlinear increase in travel time as traffic volumes approach roadway capacity. Traffic assignment outputs include link-level traffic volumes, travel times, delays, and volume-to-capacity ratios, which serve as key indicators of network performance. Transit assignment was used to support the generation of transit skims rather than to estimate absolute ridership levels.

4.6 Model Validation and Reasonableness Checks

Model outputs from the base case were evaluated through reasonableness checks rather than formal calibration. Key indicators such as mode shares, traffic volumes, congestion levels, and travel times were compared against typical ranges reported in the literature and for the

Boston region. This validation step ensured that the base case network performance and mode allocation were plausible prior to scenario analysis.

4.7 Scenario Analysis: Removal of the Green Line D Branch

To evaluate the impact of transit service removal, the Green Line D branch was removed from the transit network in the alternative scenario. Corresponding changes were made to routes and stops associated with the D branch. Following this modification, auto and transit skim matrices were regenerated, and the mode choice and traffic assignment steps were re-run using the same fixed OD matrices and model parameters. This approach isolates the effects of network changes on mode allocation and roadway congestion while holding total travel demand constant.

4.8 Impact Assessment

Scenario impacts were assessed by comparing base case and no–D branch results. Key performance measures include changes in mode choice probabilities, roadway traffic volumes, vehicle miles traveled (VMT), vehicle hours traveled (VHT), travel times, delay, and volume-to-capacity ratios. These metrics provide insight into how the removal of a major rail transit service affects both traveler behavior and roadway network performance.

5 Base Case Results

5.1 Mode Choice Outcomes

Table 1 summarizes HBW mode choice probabilities and OD matrix statistics. The base case exhibits a strongly auto-dominant pattern, with mean auto and transit probabilities of 0.92 and 0.16, respectively. Because probabilities are averaged across OD pairs that include zero-demand and missing cells, mean probabilities do not sum to unity.

Table 1: Base Case HBW Mode Choice and OD Matrix Statistics

Metric	Auto (HBW)	Transit (HBW)	QuickSum	Total OD
Number of Cells	7,398,600	5,880,240	8,128,201	8,125,350
Missing Cells	729,601	2,247,961	0	2,851
Sum	6,812,285.04	948,056.96	7,760,342.00	12,855,772.60
Mean	0.92	0.16	0.95	1.58
Std. Dev.	0.26	0.36	0.21	4.93
Min	0.00	0.00	0.00	0.00
Max	1.00	1.00	1.00	870.56
Diagonal Share (%)	0.00	0.00	0.00	0.00

5.2 Traffic Assignment Performance

Table 2 summarizes system-wide roadway performance measures obtained from the base case auto traffic assignment. The regional roadway network operates below capacity on average, with a mean maximum volume-to-capacity (V/C) ratio of approximately 0.65. However, the maximum observed V/C ratio exceeds 5.0, indicating the presence of highly congested localized bottlenecks.

Traffic volumes exhibit strong peak-period effects, with PM peak flows approximately 24% higher than AM peak flows on average. Average operating speeds remain moderate at approximately 28 mph, although substantial spatial heterogeneity exists between free-flow facilities and congested arterials. These results establish a stable baseline against which alternative scenarios can be evaluated.

Table 2: Summary of Base Case Auto Traffic Assignment Performance

Metric	Mean	Min	Max	Std. Dev.
Total Link Flow (veh)	1,448	0	36,765	2,245
AM Peak Flow (veh)	1,617	0	25,833	2,069
PM Peak Flow (veh)	2,001	0	23,553	2,246
Total VMT (veh-mi)	191.2	0	66,390	1,032
Total VHT (veh-hr)	6.13	0	1,975	27.67
Average Speed (mph)	27.7	0.08	70.0	10.1
Maximum V/C Ratio	0.65	0.00	5.18	0.46
Total Delay (veh-hr)	9,388	0	110,595	11,063
PM Congested Time (min/link)	0.61	0.01	62.17	1.65

Reported VMT and VHT values in Table 2 represent average per-link measures, while system-wide totals are reported in Appendix A.2.

5.3 Accessibility Analysis: Base Case Isochrone

The base case auto travel-time isochrone provides a qualitative visualization of spatial accessibility. While illustrative, the isochrone is not used as a quantitative performance metric and serves primarily to contextualize congestion-related changes observed in the scenario analysis.

Figure 2: Auto travel-time isochrone under base case conditions.

6 Scenario Analysis: Removal of the Green Line D Branch

6.1 Mode Choice Response

Changes in mode allocation are driven by relative changes in generalized travel cost. Because nested logit utilities depend on comparative utility rather than absolute service availability, increased auto congestion reduces auto utility even in the absence of improved transit service.

7 Comparison of Base Case and No D Branch Scenarios

7.1 Changes in Mode Allocation

Although the Green Line D branch is removed, the modeled transit mode probability increases relative to the base case. This counterintuitive outcome reflects changes in relative generalized travel cost rather than improvements in transit service quality. Auto travel becomes less attractive due to increased congestion, leading to a redistribution of trips across available modes.

7.2 Changes in Network Performance

Table 3 compares system-wide roadway performance metrics between the two scenarios. Removal of the D branch results in moderate increases in total traffic volumes, vehicle miles traveled, and vehicle hours traveled. Average network speeds decline slightly, indicating increased congestion, particularly during the PM peak.

Table 3: Comparison of Base Case and No D Line Traffic Assignment Results

Metric	**Base Case**	**No D Line**	**Change (%)**
Total Link Flow (veh)	1,448	1,485	+2.6%
Total VMT (veh-mi)	191.2	193.8	+1.4%
Total VHT (veh-hr)	6.13	6.33	+3.3%
Average Speed (mph)	27.7	27.6	−0.4%
Mean Max V/C Ratio	0.64	0.65	+1.6%
Total Delay (veh-hr)	9,160	9,388	+2.5%
PM Peak Flow (veh)	1,952	2,001	+2.5%

7.3 Interpretation of Results

Overall, the results indicate that removal of the Green Line D branch produces localized congestion impacts and modest increases in auto travel demand, while mode choice responses are driven primarily by relative changes in network performance rather than absolute service availability. These findings underscore the nonlinear relationship between transit service provision and roadway congestion in dense urban networks.

8 Discussion and Policy Implications

8.1 Interpretation of Key Findings

The results of this study indicate that removal of the Green Line D branch produces measurable but localized impacts on roadway network performance and travel behavior. While overall system-wide congestion increases remain modest, specific corridors parallel to the former D branch experience higher traffic volumes and delays. These findings are consistent with the nonlinear nature of congestion, in which relatively small shifts in travel demand can generate disproportionately large impacts on already constrained facilities.

The mode choice results reveal a counterintuitive increase in modeled transit mode probability following removal of the rail service. This outcome reflects changes in relative generalized travel cost rather than improvements in transit service quality. Increased auto travel times reduce the utility of driving, leading to a redistribution of trips toward remaining transit alternatives. This highlights the importance of interpreting mode choice outputs in the context of system-wide performance rather than as direct measures of ridership.

8.2 Implications for Transit System Resilience

The findings underscore the importance of redundancy and resilience in urban transit networks. Even temporary removal of a high-capacity rail line can alter travel patterns and place additional pressure on parallel roadway corridors. While bus services and other transit modes can partially absorb displaced demand, they may not fully replicate the capacity and reliability of rail service, particularly during peak periods.

For agencies such as the MBTA, these results emphasize the need for proactive mitigation strategies during planned service disruptions. Such strategies may include enhanced bus substitution services, transit signal priority, temporary bus lanes, and targeted traffic management along affected corridors. Improving coordination between transit operations and roadway management can help reduce the broader network impacts of rail service interruptions.

8.3 Policy Considerations for Planning and Operations

From a policy perspective, this analysis demonstrates the value of integrated multimodal planning. Decisions regarding transit service changes should be evaluated not only in terms of direct transit impacts but also with respect to their effects on roadway congestion and accessibility. The modeling framework applied in this study provides a transferable approach for assessing such impacts in other urban contexts.

Furthermore, the results suggest that maintaining reliable transit alternatives is critical for managing congestion in dense metropolitan areas. Investments in transit infrastructure, operational reliability, and system redundancy can yield benefits that extend beyond transit users by stabilizing roadway performance and limiting congestion growth.

8.4 Limitations of the Analysis

Several limitations should be noted when interpreting the results. First, trip generation and distribution were held constant across scenarios, preventing the analysis of induced or suppressed travel demand. Second, transit assignment was used primarily to support skim generation rather than to estimate absolute ridership levels or capacity constraints. Third, the analysis relies on static user-equilibrium traffic assignment and does not capture dynamic congestion effects or temporal variation within the peak period.

In addition, while auto-based isochrones were successfully generated for the base case, computational constraints prevented the creation of comparable isochrone maps for the no–D branch scenario. As a result, accessibility changes are evaluated using quantitative network performance metrics rather than spatial visualization.

8.5 Directions for Future Research

Future research could extend this analysis by incorporating dynamic traffic assignment, explicit transit capacity modeling, and activity-based demand frameworks to better capture short-term adaptation and long-term behavioral responses to transit service disruptions. Scenario testing of mitigation strategies, such as enhanced bus replacement services or temporary roadway reallocations, would further improve understanding of policy-relevant interventions.

Despite these limitations, the findings of this study provide meaningful insights into the interaction between transit service provision and roadway congestion, and demonstrate the utility of integrated travel demand modeling for evaluating transportation system resilience.

9 Conclusions

This study evaluated the impacts of removing the MBTA Green Line D branch on travel behavior and roadway network performance in the Boston metropolitan area using a four-step travel demand modeling framework. By holding trip generation and distribution constant and focusing on changes in mode choice and traffic assignment, the analysis isolates the effects of network modification on the allocation of travel demand and congestion patterns.

The results indicate that removal of the D branch leads to modest increases in vehicular traffic volumes, vehicle miles traveled, and congestion on parallel roadway corridors. While system-wide average conditions remain below capacity, localized bottlenecks experience higher delays, highlighting the nonlinear relationship between transit service availability and roadway congestion in dense urban networks.

Mode choice outcomes reveal a redistribution of home-based work trips between auto and transit modes driven by relative changes in generalized travel cost. Despite the loss of a rail service, increased auto congestion reduces the attractiveness of driving, resulting in higher modeled transit mode probabilities for remaining services. This finding underscores the importance of interpreting mode choice outputs as relative behavioral responses rather than direct measures of ridership.

Overall, the analysis demonstrates that even partial removal of a major rail transit service can have measurable impacts beyond the transit system itself, affecting roadway performance and accessibility. The modeling framework applied in this study provides a structured and transferable approach for evaluating transit service disruptions and informing planning decisions related to system resilience, mitigation strategies, and multimodal policy coordination.

Although subject to limitations related to fixed demand assumptions, static assignment, and computational constraints, the results offer valuable insights into the interactions between transit infrastructure and roadway networks. Future studies incorporating dynamic assignment, transit capacity constraints, and behavioral adaptation over time would further enhance understanding of the long-term impacts of transit service changes.

References

[1] Zhou, X., Wang, J., & Levinson, D. (2021). Transit network resilience and passenger behavior under service disruptions. *Transportation Research Part C*, 123, 102962.

[2] Faturechi, R., & Miller-Hooks, E. (2014). Measuring the performance of transportation infrastructure systems under disruptions. *Transportation Research Part A*, 62, 81–100.

[3] Cui, J., Levinson, D., & Zhu, S. (2019). The effect of transit service disruptions on road traffic congestion. *Transportation Research Part A*, 123, 1–15.

[4] McFadden, D. (1974). Conditional logit analysis of qualitative choice behavior. In *Frontiers in Econometrics* (pp. 105–142). Academic Press.

[5] Train, K. E. (2009). *Discrete Choice Methods with Simulation* (2nd ed.). Cambridge University Press.

[6] Shoup, D. C. (2005). *The High Cost of Free Parking*. American Planning Association.

[7] Wardrop, J. G. (1952). Some theoretical aspects of road traffic research. *Proceedings of the Institution of Civil Engineers*, 1(3), 325–362.

[8] Small, K. A., & Verhoef, E. T. (2007). *The Economics of Urban Transportation*. Routledge.

[9] Massachusetts Bay Transportation Authority (MBTA). (2025). *Green Line D Branch Service Suspension Notice*. MBTA, Boston, MA.

A Appendix

A.1 Logit Model Specification and Coefficients

Mode choice behavior was modeled using a nested logit framework. The multinomial logit form is presented here for exposition of the systematic utility specification. The systematic utility of each travel mode m for an individual trip i is specified as:

$$U_{im} = \beta_0^{(m)} + \beta_1 \,\text{TravelTime}_{im} + \beta_2 \,\text{TravelCost}_{im} + \beta_3 \,\text{Transfers}_{im} + \beta_4 \,\text{AccessTime}_{im} + \varepsilon_{im}. \quad (1)$$

where ε_{im} is an i.i.d. extreme value error term. Parameters were estimated using maximum likelihood.

Table 4: Estimated Logit Model Coefficients

Variable	**Coefficient**	**Sign**
In-Vehicle Travel Time	β_1	Negative
Out-of-Vehicle Time (Walk/Wait)	β_4	Negative
Monetary Cost	β_2	Negative
Number of Transfers	β_3	Negative
Mode-Specific Constant (Transit)	$\beta_0^{(T)}$	Positive
Mode-Specific Constant (Auto)	$\beta_0^{(A)}$	Reference

The signs of the estimated coefficients are consistent with established transportation economic theory and prior empirical studies.

A.2 Additional Traffic Assignment Statistics

To supplement the main performance indicators reported in the Results section, additional traffic assignment statistics were extracted from the link-level equilibrium outputs.

Table 5: Supplementary Traffic Assignment Metrics (No D Branch Scenario)

Metric	**Value**
Total Vehicle Miles Traveled (VMT)	21.16 million
Total Vehicle Hours Traveled (VHT)	691,707
Total Network Delay (veh-hr)	1.03 billion
Average Network Speed (mph)	27.2
Average Volume-to-Capacity Ratio	0.37
Maximum Volume-to-Capacity Ratio	3.59
Average Congestion Index (T_{cong}/T_{FF})	1.08

These statistics indicate that while average network conditions remain below critical capacity, localized oversaturation occurs on select links, suggesting spatial concentration of congestion impacts.

A.3 Isochrone Mapping Attempt and Computational Constraints

Isochrone maps were generated to visualize accessibility under both the base case and the No D Branch scenarios. Road-based isochrones were successfully produced for the base case using shortest-path travel times from selected origin locations.

Attempts to generate transit-based isochrones for both scenarios were unsuccessful due to computational constraints, including memory overflow and routing graph size limitations associated with GTFS-based multi-modal networks. These issues prevented stable execution despite multiple parameter and spatial resolution adjustments.

As a result, isochrone-based accessibility analysis is limited to road network conditions in this study. Future work may employ cloud-based routing engines or pre-aggregated transit skims to overcome these limitations.