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Cross-Modal Impact Assessment for Sustainable Transportation Networks

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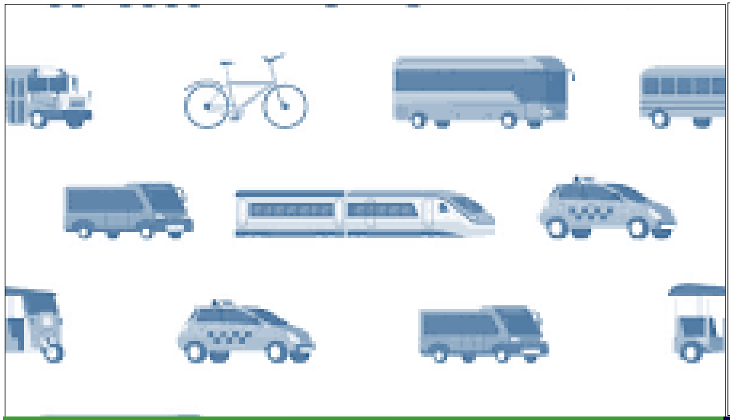

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16. Abstract It is often difficult to compare different travel modes when it comes to assessing sustainability. That is because there are many factors guiding investment to different modes of transportation and these factors may not always be comparable from one mode to another. This study aims to develop a holistic impact measurement (HIM) methodology incorporating economic, environmental, and social factors of sustainability for different transportation modes. The focus of the project is to compare the overall sustainability of a travel choice from point A to point B with a current snapshot of Massachusetts transportation infrastructure. The second focus of the project is to convert these factors to monetary costs to better quantify the importance of agency costs and subsidies on transportation. The research includes stakeholder engagement, metric selection, and case studies across various transportation modes in Massachusetts. Key findings reveal that public transit and active transportation often emerge as more sustainable options, particularly for shorter trips. A sensitivity analysis demonstrates the influence of stakeholder priorities and policy changes on sustainability metrics. The study highlights the importance of increased public transit ridership, active travel promotion, and safety improvements.		
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Cross-Modal Impact Assessment for Sustainable Transportation Networks

Final Report

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Disclaimer

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Executive Summary

This study of Cross-Modal Impact Assessment for Sustainable Transportation Networks was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Transportation infrastructure is a critical component of modern societies, affecting not only mobility but also the environment, economy, and social well-being. In recent decades, there has been a growing recognition for the need to incorporate sustainability into transportation planning and investment decisions. Traditional approaches often focus on immediate financial costs, overlooking broader implications such as long-term environmental impacts, social equity, and overall economic sustainability. As such state transportation agencies are at a crucial juncture, needing to make substantial investments in multimodal transportation systems with long-term impacts. While federal agencies such as the FHWA stresses the importance of sustainable development across environmental, social, and economic sectors, standardized evaluation methodologies are lacking. This study is motivated by the need to develop metrics for assessing the sustainability of various transportation modes, aiding state agencies in integrating sustainability into their planning processes.

Users usually have multiple choices when they decide to travel from point A to point B. However, comparing the overall sustainability of different travel modes is often difficult due to differences across these modes. These differences also make it difficult to quantify the monetary costs or gains due to agency costs or subsidies given to certain modes. This gap may lead to suboptimal use of funds, social inequities, and environmental degradation. To address these challenges, this study develops a methodology that defines and compares the sustainability of different transportation modes to provide clear and consistent information to decision-makers. To achieve this, this study focuses on a current snapshot of the transportation infrastructure in the state of Massachusetts and aims to quantify the sustainability impacts of different travel modes.

They key objectives of the study are

1. To define what impacts across economic, environmental and social aspects of sustainability should be quantified when it comes to comparing different transportation modes. These impacts are considered externalities, and the associated costs have an impact on the Commonwealth. Therefore, it is important to define and quantify the impacts to holistically understand the state transportation cost.
2. To quantify these impacts for different modes of transportation when a user decides to travel from point A to B on a per passenger per trip basis.
3. To convert these impacts to monetary costs or gains to better understand the importance of agency spending.
4. To develop a holistic impact measurement (HIM) methodology that can summarize these impacts under one number using aggregation.

5. To perform sensitivity analysis to better understand investment decisions and future scenarios.

Methodology

The project developed cross-modal sustainability metrics for transportation systems after a comprehensive literature review of published documents and discussions on important components of sustainability with stakeholders. Stakeholder input guided metric selection, ensuring practicality and relevance to MassDOT and MBTA. The chosen metrics are quantifiable, mode agnostic, and based on existing data collection capabilities. They cover economic, environmental, and social aspects, including agency costs, CO_2 emissions, travel costs, health impacts, reliability, and safety.

The key stages of the development process included:

1. Stakeholder Engagement: This initial stage involved discussions with key stakeholders through workshops and meetings to gather insights and refine the metrics derived from existing literature and assessments. The goal was to align the metrics with practical needs and MassDOT's strategic objectives.
2. Metric Selection and Quantification: The metrics were selected based on their relevance across different modes, their quantitative nature, and the availability of data. They encompass economic, environmental, and social aspects, such as agency costs, CO_2 emissions, health impacts, and safety.
3. Conversion to Cost Values: The metrics were converted into monetary values to facilitate straightforward application and comparison in policymaking and maintenance decisions. This conversion utilized a generalized formula, translating various impacts into cost implications.

Case Studies

A detailed application of the developed cross-modal sustainability metrics through four diverse case studies in Massachusetts. The studies encompass regional, local, and neighborhood trips, providing a broad perspective on transportation sustainability across various modes and distances.

The case studies examine trips ranging from 1 to 60 miles, including routes from Attleboro to Quincy Market, Quincy Market to Metropolitan Waterworks Museum, Fenway Park to Boston South Station, and Franklin Park Zoo to The Museum of Bad Art. Each case study compares multiple transportation modes, such as car, commuter rail, subway, bus, and bicycle, offering a holistic view of transportation options. Data for these metrics were sourced from reliable transportation databases and previous studies, ensuring accuracy and relevance.

Key findings from the case studies reveal significant variations in sustainability across different modes:

1. Economic Impact: Public transit has a generally higher per person per trip agency cost compared to other modes. However, this is generally due to the large number of road users compared to transit users. However, sensitivity analysis shows that increasing ridership can greatly reduce transit cost due to transit being more sensitive

to ridership.
2. Environmental Impact: Bicycling and public transit consistently demonstrate lower CO_2 emissions, with cars typically having the highest environmental cost.
3. Social Impact: While cars often provide the shortest travel times, they frequently incur higher social costs due to safety risks and negative health impacts. Bicycling, despite longer travel times, often shows the lowest overall social cost due to health benefits and zero emissions.
4. Holistic Assessment: When all factors are considered, public transit and bicycling frequently emerge as the most sustainable options, particularly for shorter trips. However, for longer regional trips, the efficiency of public transit becomes more pronounced.

Sensitivity Analysis

Weight and policy sensitivity analyses were conducted. This critical examination provides insights into how variations in stakeholder priorities and policy changes affect the sustainability metrics of different transportation modes.

The weight sensitivity analysis revealed that stakeholder-assigned weights significantly influence the final cost metrics. The scenario sensitivity analysis demonstrated how changes in key parameters, such as emission rates and ridership levels, impact the cost metrics of various transportation modes. A key finding was that increased ridership in public transit substantially reduced per-passenger costs, underscoring the importance transit usage.

Key insights from the analysis include the following:

1. Stakeholder feedback suggested placing less emphasis on the agency costs.
2. Active travel modes, particularly biking, showed substantial health benefits, emphasizing the need for policies that promote walking and cycling.
3. Improving the reliability of public transit emerged as a crucial factor in reducing costs and enhancing user satisfaction.
4. Safety improvements across all modes were highly valued by stakeholders, highlighting the importance of reducing injuries and fatalities.
5. Stakeholders placed significant emphasis on reducing the respiratory health effects of transportation.

To further refine the HIM framework and support ongoing sustainability efforts, it is crucial to update the data used in the analysis regularly and expand stakeholder participation

Assumptions and Limitations

There are various assumptions and limitations underlying the study's methodology and cost metric calculations. Some of these assumptions are the following:

1. The study focuses on current infrastructure, uses per-passenger-mile impacts for comparability, and assumes peak morning hour trips.
2. Agency costs only include operation and maintenance.
3. Only operational costs and tailpipe emissions were considered, assuming gasoline for cars and diesel for public transit. Therefore, vehicle purchasing costs were neglected.

Some limitations because of the assumptions include the following:

1. Use of national averages for some data types might not reflect regional variations.
2. Differences in collection and reporting methodologies across different modes could introduce inconsistencies including but not limited to reliability and injury data.
3. Focusing on only operation and maintenance may not represent the expansion cost of various transportation modes.

The study acknowledges these constraints and emphasizes the need for contextual interpretation of results. Future improvements could address these limitations, enhancing the metrics’ utility for sustainable transportation planning.

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List of Acronyms

Acronym	Expansion
BEES	Building for Environmental and Economic Sustainability
BMT	Bike Miles Traveled
BTS	Bureau of Transportation Statistics
CML	Centre for Environmental Science, Leiden University Methodology
CPI	Consumer Price Index
DOT	Department of Transportation
EIO-LCA	Economic Input-Output Life Cycle Assessment
EPA	Environmental Protection Agency
FAST-Act	Fixing America's Surface Transportation Act
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GIS	Geographic Information System
GTCF	Generalized Travel Cost Function
HIM	Holistic Impact Metric
HR	Hour
HW	Highway
IIJA	Infrastructure Investment and Jobs Act
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCIA	Life Cycle Impact Assessment
Mass GIS	Massachusetts Bureau of Geographic Information
MassDOT	Massachusetts Department of Transportation
MBTA	Massachusetts Bay Transportation Authority
MIN	Minutes
MOVES	Motor Vehicle Emission Simulator
NTD	National Transit Database
OPMI	Office of Performance Management and Innovation
$PM_{2.5}$	Particulate Matter
PMT	Passenger Miles Traveled
Q&A	Questions and Answers
SoSus	Social Sustainability
TBL	Triple Bottom Line
US	United States
VMT	Vehicle Miles Traveled

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1.0 Introduction

This study of Cross-Modal Impact Assessment for Sustainable Transportation Networks was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

State agencies are at a crossroads, needing to make significant operational and capital investments in multimodal transportation systems, which will have far-reaching impacts (1). However, a clear methodology for modeling a comprehensive, state-specific impact assessment that addresses environmental, social, and economic factors remains elusive. As state agencies navigate a shifting funding landscape toward sustainable transportation, it is crucial to have a methodology that defines and compares the sustainability and costs of various transportation investments, considering both direct and indirect government costs. Transportation agencies can better integrate sustainability into their planning through performance measures, which provide quantified evidence of the outcomes of actions (2,3). By translating data into a clear and consistent format, critical information is effectively conveyed to decision-makers.

The FHWA has emphasized the need for sustainable development across environmental, social, and economic sectors (4). Yet, there are not standardized methodologies to evaluate the holistic impacts of their transportation investments. Without this, decisions may lead to suboptimal use of funds, exacerbating social inequities, and environmental degradation.

At the federal level, the necessity of this study is underscored by two recent legislative efforts: The Infrastructure Investment and Jobs Act (IIJA) and the Fixing America's Surface Transportation (FAST) Act. The IIJA, also known as the Bipartisan Infrastructure Law, was enacted in November 2021 and aims to rebuild America's infrastructure with a focus on sustainability, resilience, and equity. It includes significant investments in public transit, electric vehicle infrastructure, and initiatives to reduce greenhouse gas emissions from the transportation sector (5). The FAST-Act, enacted in December 2015, was the first federal law in over a decade to provide long-term funding certainty for surface transportation infrastructure planning and investment. It established performance-based programs that emphasize the importance of sustainability metrics, such as reducing environmental impacts and improving air quality (6). Both bills highlight the importance of developing sustainability metrics to guide data-driven transportation investments, ensuring that federal funds are used efficiently and effectively to support sustainable development goals.

In today's rapidly evolving world, transportation infrastructure is more critical than ever. The pressures of climate change, increasing public health concerns, and fluctuating economic conditions demand that we rethink how we invest in transportation (7). Traditional approaches often focus on immediate upfront financial costs, neglecting broader implications such as long-term environmental impacts, social equity, and overall economic sustainability.

Though urban growth led to the expansion of transportation systems in the 20th century, it has also presented obstacles to sustainability attainment (8). According to Illahi and Mir (8), there has been a more than 43% increase in global car ownership in 19 years (2000–2019), which persistently contributes to environmental degradation, particularly through increased air pollution and greenhouse gas emissions. This surge in car ownership exacerbates air quality issues and contributes significantly to climate change, making the environment less sustainable. Moreover, the increase in car ownership has social implications, such as increased traffic congestion, which reduces the quality of life and can lead to higher rates of accidents and road fatalities. It also exacerbates social inequities, as lower-income communities often suffer disproportionately from the adverse effects of traffic, including noise pollution and reduced access to clean air and green spaces.

Economically, the rising number of cars on the road leads to higher maintenance costs for infrastructure, including roads and bridges. It also increases the economic burden on individuals due to higher fuel consumption and vehicle maintenance costs. In the long run, the economic sustainability of relying heavily on private car ownership is questionable, given the significant public funds required to support this mode of transportation and the economic costs associated with environmental and health impacts.

Infrastructure deterioration has led federal governments to ensure more sustainable transportation systems by advocating and implementing public or multimodal transportation policies. Transport infrastructure has been labeled a major contributor to worldwide carbon emissions (1,9). In a span of three decades, carbon emissions from transportation have increased more than any other sector. According to the US Environmental Protection Agency (EPA), this makes transportation the largest contributor of greenhouse gas (GHG) emissions in the United States with about 29% (10). Therefore, creating and promoting the sustainability of multimodal transportation systems is especially salient.

All three dimensions of sustainability (economic, environmental and social) must be adequately prioritized within transportation agencies and responsible parties (11,12). Although much focus has not been given to the social aspect of sustainability. These dimensions of sustainability are generically known as the triple bottom line (TBL) (13). TBL is often represented by the three P's: profit, planet, and people. This framework recognizes that the success of a system should not be solely measured by financial profit but also by its impact on the environment(planet) and the well-being of individuals and society (people). The TBL framework has proven valuable for seeking a sustainable path (14).

A "sustainable transportation system" lacks a single, universally accepted definition. However, the Transportation Research Board (3) defines it as a system that meets essential access and development needs safely and promotes equity across generations. It should be affordable, efficient, offer multiple transportation modes, and support a competitive economy and balanced regional development. Additionally, it should minimize emissions, waste, and resource use, ensuring they remain within the planet's capacity to absorb them, and use resources at sustainable rates.

Although some widely accepted guidelines and standards for sustainable transportation metrics in the United States are used by the US Department of Transportation (such as TRACI for environmental impact assessment and the Life Cycle Cost Analysis (LCCA) Primer published by FHWA's pavements program), many state DOTs have metrics tailored to their specific needs (15,16,17).

However, these tools predominantly focus on environmental and economic sustainability without providing a clear distinction on social sustainability metrics. In our study, we emphasize that social sustainability encompasses more than just user costs. Social sustainability is often understudied and lacks robust, quantifiable tools, making it challenging to comprehensively assess the social impacts of transportation investments. This underscores the need for developing metrics that can capture the social dimension of sustainability. Addressing this is essential for making informed transportation investment decisions that truly reflect the triple bottom line of sustainability: economic, environmental, and social impacts.

Although there have been many developments for individual modes, no standard metric has been established for assessing or quantifying the sustainability of cross-modal transport impacts. The first step of sustainable transportation is a measure of comparison of various transportation modes in determining where future investments should be focused. This research is motivated by the need to determine the metrics for assessing the sustainability of different transport modes from point A to B, which will be used in quantifying the cross-modal sustainability of various modes.

1.1 Objectives and Roadmap

The study has the following objectives:

1. Identify the key metrics for cross-modal impact assessment of sustainable transport networks considering economic, environmental and social dimensions of sustainability.
2. Collection of data and quantifying sustainability of different case studies using identified metrics to showcase the use of the methodology for quantifying sustainability for any travel from point A to point B.
3. Development a HIM using a methodology that is repeatable and can be readily incorporated into existing MassDOT procedures.
4. Perform sensitivity analysis for future scenarios.

The rest of the project is structured as follows.

Section 2 conducts a literature review of the three dimensions of sustainability. The three dimensions of sustainability are economic, environmental and social. The various metrics for sustainable transportation across dimensions are highlighted and discussed. This section ends with an important components table summarizing the impacts that are selected and used in this study after literature review.

Section 3 describes the development of cross-modal sustainability metrics, detailing stakeholder engagement and the rationale for selecting a smaller subset of metrics for practical purposes. The final list of quantifiable metrics is provided, along with descriptions and methods for converting each metric to a cost value.

Section 4 presents case studies used in the study, including data sources and methodologies tailored to each case study. The final numbers and explanations for each case study, showing the quantified sustainability impacts are also shown.

Section 5 is the sensitivity analysis for the case studies, examining how changes in metrics and weights proposed by different stakeholders affect the final cost metric. It concludes with actions for improved metrics.

Section 6 discusses the assumptions made for different cost metrics, the limitations of the study, and the ranges for use. It concludes with future consideration for weights and methods selection.

2.0 Impact Selection for Comparison Across Transportation Modes

2.1 Literature Review

This section is structured into three main parts, each dedicated to one of the pillars of sustainability. The first section addresses economic sustainability, exploring the financial impacts and metrics used to evaluate the cost-effectiveness and economic benefits of transportation systems. The second section delves into environmental sustainability, discussing the environmental impacts and the metrics employed to assess the ecological footprint of various transportation modes. The third section focuses on social sustainability, examining the social impacts and metrics.

2.1.1 Economic Sustainability

Definition of economic sustainability in transportation systems

The preservation of constant or increasing financial well-being characterizes economic sustainability. This concept revolves around efficiently allocating savings and investments to ensure the highest level of prosperity for both current and future generations (18,19). Jurigová et al. (20) argue that economic sustainability focuses on the effective use of resources, financial performance, and the long-term profitability of a project or company. Therefore, the role of economic analysis is crucial in any managerial decision-making process. To achieve economic sustainability, it is essential to make fair, unbiased, and financially responsible decisions while also considering other aspects of sustainability (21). The economic dimension is a crucial part of sustainability that supports the survival and progress of an institution (public or private) (22)

It holds greater significance in many contexts because it directly relates to the institutions' interests and existence (23).

In the case of transportation, economic sustainability can be said to be focused on the cost and benefits of any transportation mode. Shi et al. emphasize that the efficient allocation of federal or public funds can foster urban transportation and contribute to the safety, accessibility, and innovative aspects of sustainable transportation systems (24). Economic sustainability in transportation lies in its propensity to be financially stable in the long run while ensuring viable investments and its benefits to various stakeholders through strategic planning and decision-making.

Components of economic sustainability

According to Castillo and Pitfield (25), a sustainable transport system should support economic growth and consider the full range of costs associated with transportation activities. To make informed decisions regarding transport policies and planning, communities require precise and comprehensive information about the costs associated with transportation, as highlighted by Litman (26). Popovic et al. (27) identify economic costs, specifically capital and operating costs, as crucial components for assessing financial sustainability. Capital costs refer to the expenses involved in establishing or initiating transport infrastructure, while operating costs encompass the ongoing expenses related to the regular usage and maintenance of the infrastructure. Rodrigue and Notteboom (28) also expound transport costs as the financial burdens that transport service providers and users bear internally. These costs consist of fixed costs, which pertain to infrastructure, and variable costs, which are associated with the day-to-day operations of the transportation system. Fixed costs encompass expenses related to the construction and maintenance of transportation infrastructure. In contrast, the Generalized Travel Cost Function (GTCF) or variable costs include the reliability of trip travel time, comfort, privacy, tolls, transit fares, fuel consumption, and maintenance expenses incurred during the use of transport services. By considering both fixed and variable costs, one can understand the financial implications of transportation. Jakob et al. (29) claim that economic costs associated with transportation are categorized into internal cost (paid) and external cost (unpaid). Internal costs are costs incurred by the government to provide a transport system. Users also incur internal operating costs, including vehicle costs, insurance, repairs, congestion, and user fees. External costs associated with transportation are not incurred by individual transport users but rather by society and the environment.

The FHWA Primer (17) states that transportation costs can be classified as agency costs and user costs. They assert that these two costs are the basis for any LCCA. Agency cost pertains to the financial expenses incurred by the responsible agency for constructing and maintaining transport infrastructure. The agency costs are directly impacted by material prices, labor expenses, and equipment-related outlays, which directly influence the financial burden carried by the agency, including the uncertainty of future cost of maintenance. The user costs are the financial burdens incurred by the users of any transportation infrastructure. In essence, user costs represent the monetary and time-related consequences experienced by road users arising from vehicle operating costs (increased fuel consumption, repair, maintenance, insurance), time lost due to congestion or delays, costs associated with accidents, and the environmental impact of vehicle emissions (30).

Economic sustainability includes any cost associated with a monetary value (dollar amount). Some additional costs are difficult to quantify in monetary terms, including user comfort, noise, physical activity, and emissions. Assigning a specific monetary value to these costs is challenging, often leading to their neglect or omission in cost assessments. These costs usually directly impact social or environmental sustainability and are classified as such in our proposed cross-dimension, cross-modal approach in Section 3.

Quantification metrics for economic sustainability

Quantification of economic sustainability involves expressing or measuring components in numerical or monetary terms. Measuring sustainability is challenging due to its mix of qualitative (e.g., comfort) and quantitative (e.g., fuel cost) elements. LCCA is a well-known tool used to quantify the economic sustainability of transport infrastructure by considering all costs involved in acquiring, maintaining, and operating the system. LCCA is beneficial for comparing transport systems that meet the same performance requirements but differ in initial and operating costs (31). The objective is to identify the option that maximizes net savings.

The FHWA defines a "project" in transportation as an investment made by an agency to meet specific performance requirements for the public, whereas a "project alternative" is a proposed solution to achieve the same performance level. The difference in costs becomes the key factor in evaluating and choosing among alternatives. The FHWA recommends using the present value (PV) approach, also known as the "present worth" method, for evaluating costs. The equivalent uniform annual cost (EUAC) approach is also widely used (17). LCCA can be broken down into agency and user costs.

Agency Costs: Agency costs in transportation include preliminary engineering, contract administration, production, construction, maintenance and repair, transportation of materials and equipment, and end-of-life (EOL) considerations (32). These costs are calculated by considering both present and anticipated future expenses related to the agency's responsibilities (33,34). The discount rate, adjusted to the present year using a real discount rate, converts future costs into equivalent annual amounts. State departments of transportation (DOTs) use LCCA to select the most economically viable project alternatives, especially for new construction or reconstruction of roadways, allowing comparison of net present values (NPVs) between different investments (35).

User Costs: Users pay for the cost of owning and operating a vehicle or fares for public transport. Other costs include congestion, pollution, emissions, private parking lot construction, injuries, and deaths from vehicle-involved collisions. User costs are the expenses incurred by the public during the use and operation of vehicles, including travel time. Road user costs (RUC) are commonly categorized as a summation of work zone delay costs (WZDCs), vehicle operating costs (VOCs), and accident costs (AC) (30,36).

Vehicle Operating Costs: VOC encompasses expenses associated with consuming various resources during vehicle operation. Common VOC models include the US EPA's Motor Vehicle Emission Simulator (MOVES), the National Cooperative Highway Research Program (NCHRP) Report method, and the Texas Research and Development Foundation method. These models help assess the impact of traffic changes on resource consumption, including emissions, and provide insights for managing and mitigating VOC-related costs (30,36).

Work Zone Delay Costs: These costs are computed by considering waiting times during peak hours, the value of time (VOT), and inadequate services during off-peak hours or holidays (37). Travel delay costs are determined by multiplying estimated delays in personal travel by the unit cost of travel time ($/hr) (33).

Accident or Crash Costs: Accident costs are typically caused by human factors, vehicle factors, and external or road environment factors (38,39). Work zones can increase the likelihood of crashes; hence transportation professionals use a crash modification factor (CMF) to estimate crash rates during work zones (33). Roadway crashes are categorized based on severity: fatal crash, injury crash, and Property Damage Only (PDO) (30).

Travel Time: Travel time refers to the time it takes to travel from one location to another using any mode of transportation, such as cars, buses, or trains (39,40).Travel time costs are quantified using economic productivity, revealed or stated preference, and travel impact modeling (40–43)**.**

2.1.2 Environmental Sustainability

Environmental sustainability is the ability to meet present and future resource requirements without harming the ecosystems that provide them, emphasizing the importance of maintaining biological diversity (44). An Environmentally sustainable transport system strives to minimize the negative environmental impact by responsibly managing renewable and nonrenewable resources and promoting the development and utilization of renewable alternatives (45).

The transportation sector is a major source of pollutants such as greenhouse gases, nitrogen oxides, sulfur oxides, particulate matter, and volatile organic compounds, which have immediate and long-term effects on the environment and human health (46). It accounts for 28.7% of total energy consumption, mainly from fossil fuels like gasoline and diesel (10,47).

Components of environmental sustainability

The transportation sector is a significant contributor to anthropogenic pollutants released into the environment due to human activities. These pollutants can include greenhouse gases (such as carbon dioxide and methane), nitrogen oxides, sulfur oxides, particulate matter, and volatile organic compounds. Other components include noise pollution, poor air quality, and waste generation which affect climate change in the long run (46,48). Additionally, Van Fan et al. stipulate that air pollutants, including carbon monoxide (CO), lead (Pb), volatile organic compounds, sulfur oxides (SOx), and nitrogen oxides (NOx), have immediate effects on the environment and human health (49). These pollutants produce secondary pollutants such as ozone (O3) and particulate matter (PM). In the atmosphere, they can also lead to the formation of haze or smog. Additionally, air pollutants can impair visibility and contribute to acidification.

Transportation emissions can occur during various life cycle stages, including construction, maintenance, use, and end of life. Each stage has its own set of emissions, and upstream and downstream activities significantly influence emissions throughout the life cycle. The construction phase involves building vehicles, infrastructure, and related facilities. It contributes to emissions through manufacturing processes, material extraction, and transportation of construction materials. Maintenance activities, including repairs and regular servicing, contribute to emissions through energy consumption, replacement parts, and associated processes. Road or rail construction involves using materials and energy, leading to emissions and construction waste. Maintenance activities can also result in emissions and waste generation. During operation, vehicles emit greenhouse gases and air pollutants, while waste is produced from vehicle exhaust, tire wear, and other sources. Sustainable practices can be implemented to address these impacts, such as using eco-friendly materials, promoting energy-efficient technologies, and adopting effective waste management strategies.

Understanding the emissions associated with each life-cycle stage and considering both upstream and downstream factors is crucial for implementing effective strategies to mitigate environmental impacts in the transportation sector. This includes promoting cleaner fuel options, improving vehicle efficiency, implementing sustainable maintenance practices, and adopting proper end-of-life management techniques (49–51)**.**

Poor urban air quality, resulting from activities such as coal-burning power plants and transportation, has caused significant health issues, including deaths. Reducing carbon emissions is beneficial for both air quality and overall health. Climate change is expected to worsen asthma and allergies by extending pollen seasons. Additionally, global warming is likely to increase wildfires and dust storms, releasing particulate matter that harms air quality and health. By transitioning to cleaner energy sources, promoting sustainable transportation options, and implementing pollution reduction measures, we can improve air quality and minimize associated health risks. Furthermore, mitigating climate change can help alleviate the impacts of extended pollen seasons, wildfires, and dust storms, thus improving respiratory health and overall well-being.

Quantification Metrics for Environmental Sustainability

Environmental sustainability metrics are essential for assessing and improving environmental transportation performance. By using these metrics, organizations can track progress, set targets, compare performance against industry benchmarks, and identify areas for improvement.

Life-Cycle Assessment (LCA) evaluates the environmental impacts of transportation projects by considering factors like energy usage, emissions, and waste generation throughout a project's life cycle (*23*). Recognized methods for environmental impact assessment include:

- **TRACI** (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts): Developed by the US Environmental Protection Agency, TRACI is widely used in North America and provides an expanded range of stressors for quantification (15,16)
- **CML** (Centre for Environmental Science, Leiden University) Methodology**:** A comprehensive Life-Cycle Impact Assessment (LCIA) methodology that relies on European data. It is highly regarded for its thorough environmental impact factors (*28*)
- **BEES** (Building for Environmental and Economic Sustainability): Primarily evaluates the environmental and economic performance of building products, but its principles can be extended to evaluate construction products for roads (52).

Other Tools and Approaches are (53–57)***:***

- **MOVES** (Motor Vehicle Emission Simulator): Used to estimate emissions from on-road vehicles and evaluate the impact of different transportation policies and technologies.
- **PaLATE** (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects): Assesses the environmental and economic impacts of pavement construction and maintenance.
- **EIO-LCA** (Economic Input-Output Life-Cycle Assessment): Analyzes the environmental impacts of economic activities, providing insights into the broader environmental effects of transportation infrastructure.

Each of these tools has specific use cases and regional applications, making them suitable for different aspects of transportation sustainability assessment. TRACI and CML are comprehensive methods for life cycle impact assessment, focusing on regional data from North America and Europe, respectively. BEES extends the evaluation to building products and can be adapted for road construction materials. MOVES, PaLATE, and EIO-LCA offer specialized assessments for vehicle emissions, pavement impacts, and broader economic activities.

2.1.3 Social Sustainability

Social sustainability involves identifying and managing the effects, both positive and negative, that systems, processes, organizations, and activities have on people and social life (58). It aims to ensure the well-being and quality of life for individuals and communities. It is also defined as meeting human needs and fulfilling aspirations for a better life (2).
In transportation, social sustainability focuses on designing systems that prioritize people's needs, promote equitable access to mobility, improve public health, and foster strong communities (8,29). This includes ensuring affordable and accessible transportation options, reducing air and noise pollution, enhancing pedestrian and cyclist safety, and providing services to marginalized communities. Despite its importance, social sustainability is often understudied compared to economic and environmental sustainability due to its complexity, lack of awareness, the short-term focus on immediate gains and political priorities (47,59,60). Social sustainability is multidimensional and lacks a universally agreed-upon definition. However, several key components have been identified within the context of transportation. Table 2.1 summarizes these components from the viewpoint of transportation, acknowledging that this may not be a comprehensive list but rather a starting point for understanding social sustainability in this sector. These components are discussed further below.

Components of social sustainability
Amartya Sen's capability approach significantly shapes the understanding of social sustainability by focusing on the enhancement of individual freedoms and capabilities, which are essential for fostering a sustainable society (61)This framework extends the concept of quality of life to encompass not only basic needs like healthcare, education, and a clean environment, but also the freedoms that allow individuals to pursue their own goals (62). It emphasizes the importance of reducing inequalities by tailoring policies to the diverse capabilities of individuals, ensuring that everyone has equitable opportunities to succeed

(63,64). Moreover, Sen’s approach highlights the role of social cohesion, advocating for the inclusion of various cultural and social backgrounds to achieve collective well-being. This promotes diversity within communities, enhancing their resilience and adaptability to social and economic challenges (65). Additionally, the capability approach calls for participatory governance that respects individual agency in decision-making processes, making governance structures more inclusive and responsive (62). Integrating these principles into social sustainability strategies ensures that development is not only inclusive but also equitable, ultimately capable of supporting the well-being of all community members over time. These principles play a critical role in reinforcing the foundations of social sustainability.

Central to social sustainability, equality involves reducing disadvantages for certain groups, helping them overcome barriers, and addressing the root causes of these disadvantages (66). It aims to create a fair and just society where everyone has equal opportunities and access to resources, regardless of background or circumstances. Diversity strengthens recognizes and values the unique needs and contributions of different groups, enhancing social cohesion and innovation (67,68). Embracing diversity further allows society to harness its benefits for individuals and communities. Democracy on the other hand involves public participation, accountability, and considering everyone’s needs.

In transportation, social cohesion means ensuring that different groups can actively participate and access essential transit facilities (66,80). It involves building connections, encouraging and creating an inclusive and harmonious society. The provision of sidewalks, local parks, and public transit can achieve this (66). Similarly, governance in transportation entails managing and overseeing transportation systems effectively in terms of budget use and resources. Democracy is to create a fair and accessible transportation system that benefits all members of society (70).

In urban planning, social sustainability has a been describes into physical and nonphysical components which includes education and training, safety, employment, accessibility, social justice, pedestrian-friendly neighborhoods, health and well-being, and fair distribution (71). Similarly, Cuthill’s social sustainability framework developed four key elements: social justice and equity, social infrastructure, governance, and social capital (72).

Several studies have identified key components of social sustainability (SoSus) in transportation, including mobility, jobs, safety, health, access, choice, and equity. These components are often analyzed with a focus on safety, accessibility, and public health (71,73). Stefaniec et al., Haghshenas and Vaziri, and Mahdinia et al. all emphasized safety and accessibility (12,74,75) while Jeon et al. highlighted equity and public health (60). Reisi et al. included mortality from air pollution, and Zheng et al. focused on air quality impacts on health (76,77). Miller et al. (78) and Smith et al. (73) examined the disease burden from transit pollutants and noise levels.

Quantification metrics for social sustainability

Quantifying and assessing social sustainability is challenging, and much work is still needed to refine the approach (79). Most studies have either measured social sustainability components quantitatively or qualitatively. Quantitative measurement uses numerical and statistical analysis, whereas qualitative measurement relies on descriptive and narrative data to understand the experiences, perceptions, and impacts on individuals and communities. Qualitative components/metrics include gathering feedback through interviews and focus groups. Various factors influence social costs in transportation and can vary based on location, time of day, and vehicle performance (80). Due to the complexities involved, researchers create uncertainty bounds to calculate average values, providing a more balanced estimate of these costs.

There could be many measures of the components of social sustainability across many indicators. For the components of safety, accessibility, diversity, affordability, health and noise, some metrics identified in the literature are explained next.

Safety can be measured by traffic fatalities, crashes per mile, and public feedback on perceived safety (12,72,78,81). Accessibility can be measured by the length of the transport system and the number of available transit modes. Mobility can be assessed through travel time and passenger/mile. congestion cost based on the cost of delays per hour, considering factors like lost productivity and missed appointments (73). Diversity can be evaluated by the variety of transportation modes available (74). Affordability can be quantified by transit costs as a percentage of household income (66,82). Health impact can be evaluated through the cost of healthcare services, sick days, and premature deaths (80). Gössling and Choi assessed noise through the use of contingent valuation and hedonic pricing methods (80). They added that health issues related to traffic noise are assessed using national health evaluations, which include the cost of healthcare services, sick days, and premature deaths. These costs are then integrated with the number of miles driven by cars and public transit per year to estimate the overall economic impact of noise on health. By implementing these metrics and focusing on social sustainability, transportation systems can be designed to improve the well-being, equity, and inclusion of all community members.

Table 2.1 Transportation social sustainability components

Component	**Objective**	**References**
Safety	Minimize risk of crashes	(71,74,83,84)
Accessibility	Increase accessibility and mobility	(59,71,74,75,83–85)
Mobility	Freedom of passenger or vehicle movement	(12)
Jobs	Creation of job opportunities	(12,73,86)
Health	Reduction in emissions	(70,73,78,84)
Education	Promotion of access to education	(71)
Affordability	Adjust fare by income	(60,72,76,78)
Cohesion	Promotion of sidewalks and local parks	(69,71,86)

2.2 Important Impacts

The literature review identified several important components critical to understanding the sustainability of transportation systems. These components were refined through stakeholder engagement to develop a practical and applicable set of metrics for MassDOT in Section 3. Table 2.2 summarizes the important components identified in the literature review, which form the foundation for the subsequent development of quantifiable sustainability metrics. These important components are crucial to the functioning and assessment of every transportation mode, their impacts are essential. Components are split into three dimensions: economic (impact to agency), environmental (impact to environment), and social (impact to humans). Social impacts are further separated into impact to the trip taker and impact to other humans to differentiate the impacts to the person deciding to take the trip and other people affected by that decision. It is important to note that all economic impacts incurred by the user were listed under social impacts and not economic impacts as this analysis is done through an agency lens. The definitions of important impacts/components are described next.

Economic Dimension
Direct Agency Cost refers to the adjusted total maintenance and operation cost borne by the agency in charge. It represents the expense of owning(operation) and upkeeping(maintaining) a mode system.

Environmental Dimension
Emissions encompass the discharges harmful to the environment (air, water, soil), impacting climate change and causing environmental degradation. There are many emission categories such as carbon dioxide, methane ozone depletion, climate change, acidification, eutrophication, and smog formation.

Land Use is crucial because it directly correlates with sustainable development. Efficient land use minimizes ecological footprints, impervious surface area needed for supporting infrastructure, and can contribute to more environmentally friendly developments.

Social Impact to Trip Taker
Efficient Transportation measures the mobility of the transport mode. Several factors could be considered including the travel time to the point of interest, the number of transfers needed (for transit), and the congestion time.

Affordability (Travel burden) refers to the ability of the trip taker to pay for the trip. The trip taker’s ability to pay is a function of multiple factors including income, trip cost (including all expenditures such as fares, fuel, insurance, vehicle ownership, and parking), housing costs, and family size.

Physical Accessibility (Access to mode) is the ease with which individuals can access or reach and use a mode. It can be classified into general accessibility barriers and disability accessibility. General accessibility barriers are broader factors that can vary significantly from one individual to another, impacting their ability to use transportation systems. These barriers can prevent a person from making a trip altogether. Examples include time constraints, safety concerns, inaccessible stops (due to damage to supporting infrastructure). Disability accessibility refers to the specific features and equipment that facilitate the use of transportation systems by individuals with disabilities. Examples include elevators, ramps, and, wheeled mobility devices.

Perceived safety and security are factors that can significantly influence how safe and secure individuals feel when accessing and using a transportation system. Examples include dim lighting, crime rate, crash/injury rate, emergency protocols, threat of verbal or physical harassment. Perceived safety may vary for individuals and groups. For example, past research has shown that women have higher rates of anxiety while waiting for public transit (87–89).

Health mode choices promote active travel (walking/cycling) time which has been shown to increase physical health and well-being.

Reliability as an impact to the trip taker pertains to the consistency of the chosen mode. Ensuring transportation reliability improves overall system performance and enhances user satisfaction.

One of the many factors that influence user's mode choice is the *comfort and/or convenience* of the mode for a given trip. Factors include (but are not limited to) crowding/space limitations, trip flexibility, and productive time. Crowding describes situations where a public transport vehicle's passenger count surpasses its comfort and space limit, causing passenger discomfort, service inefficiency, and potential transit delays. Trip flexibility/frequency refers to how much freedom/adaptability to change trip plans in terms of time. It means how often a mode makes a particular trip/journey in an hour or day. Trip flexibility is high for driving, buses and the subway. It is low for the commuter rail. Productive time refers to time that can be utilized productively, such as for reading, writing, or checking emails. Productive time while driving is always assumed to be zero. The potential for using travel time effectively is a value-added aspect of public transport.

Social Impact to other Humans

Safety refers to the risk of bodily harm of a chosen mode on the wider population. It could be broken down into fatalities and injuries. Fatalities measure the predicted loss of life on a route, based on annual statistics for the mode. For instance, one fatality resulting from 1,000 miles of driving translates to a rate of 1/1,000 per mile. Injuries refer to the physical harm or damage to individuals resulting from accidents or incidents associated with various modes of transport. Safety issues can be reduced through increased safety features such as airbag, seat belt, guardrails, signage, pedestrian crossings, traffic laws (speed limit, traffic lights) and emergency response (fire, ambulance, police).

Health refers to the long-term health impacts of a chosen mode of transport due to that mode's emissions impact on health. It could be measured in emissions into air, soil, water as well as noise pollution. For instance, one measure of respiratory health could be fine particulate matter (particles sized 2.5 microns or below) and can harm both the lungs and heart. Exposure has been linked to numerous health issues, including premature death nonfatal heart attacks, irregular heart rhythms, exacerbated asthma symptoms, diminished lung capacity, and other respiratory symptoms.

Table 2.2 Important components

Dimension	**Impact/Component**	**Subcomponents**
Economic: Impact to Agency	Direct Agency Cost	Public transport subsidies, Adjusted maintenance cost, operation cost ($), modernization cost ($)
Environmental: Impact to Environment	Emissions	Smog, ozone depletion, acidification, carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), fluorinated gases
	Land use	Green spaces, environmental value, impervious surfaces
Social Impact to Trip Taker	Efficient transportation	Travel time, direct routes and connectivity by reducing wait times, detours, stops, transfers
	Physical Accessibility (Access to mode)	Disability Accessibility (elevators, escalators, on board ramps, wheeled mobility devices, straps)
	Physical Accessibility (Access to mode)	General accessibility barriers (t time constraints, inaccessible stops, etc.)
	Affordability (in relation to income)	Direct cost (ownership cost, parking), indirect cost (fares, monthly passes, parking)
	Physical activity	Active travel (walking, cycling, use of scooters), infrastructure availability
	Reliability	Delay time and variation in delay time
	Perceived safety	Dim lighting, dark corners
	Perceived security	Theft, violence, Emergency protocols (CCTV, alarm buttons, police nearby), harassment
	Comfort/Convenience	Productive time (effective use of travel time)
	Comfort/Convenience	Noise and distractions
	Comfort/Convenience	Crowding (limited spaces for individuals, families (with kids), groceries)
	Comfort/Convenience	Ergonomic transit design (pull-cords, handlebar design, straps)
	Comfort/Convenience	Trip flexibility/ frequency
Social Impact to Other Humans	Social Cohesion & Interaction	Diverse interactions through multiple stops along route, networking and socializing, ridership
	Safety	Accidents, injuries, loss of life, safety features such as airbag, seat belt, guardrails, signage, pedestrian crossings, driver/operator training, traffic laws (speed limit, traffic lights), emergency response (fire, ambulance, police)
	Health	Pollutants and exhaust emissions such as particulate matter (PM2.5), ground level ozone, carbon monoxide, Indoor air pollution

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3.0 Cross-Modal Sustainability Metric Development

The previous section summarized the creation of important impacts for multimodal transportation. However, not all those impacts are quantifiable using available data collection methods. Moreover, some can be only described using qualitative statements. To create a list of metrics that are suitable for quantitative analysis, the list of important components was refined down to quantifiable components which can be quantified using existing MassDOT data collection procedures after multiple rounds of stakeholder engagement. These quantifiable metrics are developed through extensive stakeholder engagement and are tailored to ensure they are practical, measurable, and relevant to the specific needs of MassDOT. Furthermore, because one of the main objectives of this study was to develop a holistic metric, this section also explains the methods used to convert these metrics into quantifiable cost values, providing a comprehensive framework for evaluating the sustainability of various transportation modes using one metric.

3.1 Quantifiable Cross-Modal Sustainability Metrics

The development of cross-modal sustainability metrics began with engaging key stakeholders to understand their needs and priorities. This process is crucial as it ensures that the selected metrics are practical, applicable for decision-making, and based on data already collected by MassDOT.

To support MassDOT's goal for sustainable and efficient transportation, we conducted stakeholder workshops and focus meetings. These sessions aimed to refine important components identified from literature and existing assessment methods. We focused on components critical to the agency's operations, particularly those that are influenceable by policy and quantifiable (i.e., can be converted into a monetary cost).

Stakeholders emphasized selecting metrics that are both impactful and measurable, ensuring alignment with MassDOT's strategic objectives. Although we identified several important components, not all were readily available or measured by MassDOT. After multiple rounds of stakeholder sessions, we narrowed the list to quantifiable components that MassDOT can measure with current methods.

The selection process was guided by input from MBTA, OPMI, and MassDOT to promote effective implementation. Many metrics were chosen because:

1. MBTA/MassDOT already collects the data.
2. Existing software was identified to facilitate quantification.
3. They are mode-agnostic to facilitate cross-modal comparison.
4. They are quantitative, allowing them to be combined into a single component score for policy and maintenance decisions.

In this research, as mentioned in the previous section, the economic metrics focuses only on the impact to the agency. User costs are considered a social metric. This distinction is made for two reasons. First, this study and approach is designed for state agencies and their cost often outweighs user cost (in monetary units). Second, social sustainability requires that a transportation mode be accessible to all, and the user cost is a salient aspect that must be considered. The emphasis on the economic dimension is on understanding how government expenditures impact multimodal transportation sustainability. Agency cost varies depending on the transit infrastructure construction, maintenance and demolition.

Social components were split into two categories: impact to the trip taker and impact to other humans. This split is to distinguish between costs to the user (e.g., fares, fuel cost) and costs that the trip taker may impose on surrounding humans (e.g., air pollution, safety).
For environmental dimension, greenhouse gases (GHG) (measured in CO_2e) were used. The components that did not have a direct measurable value (e.g. Perceived safety) were omitted from the final list of metrics. For this study, quantifiable components are components that are important and can be measured or expressed in monetary values. This allows for quantitative analysis and comparison, performance evaluation and data-driven decision-making. Costs are converted to the present value (i.e., 2023 USD).

Table 3.1 summarizes the quantifiable metrics identified through stakeholder engagement and literature review. These metrics were chosen based on their relevance to MassDOT's strategic objectives, the availability of data, and the feasibility of quantification. Each metric is designed to be mode-agnostic, facilitating cross-modal comparisons and enabling a comprehensive assessment of transportation sustainability. Importantly, each metric is standardized on a per passenger per trip basis to ensure comparability across different modes of transportation. They are quantitative, allowing them to be combined into a single component score to inform policy and maintenance decisions. Table 3.2 shows the final list of quantifiable components. These metrics are categorized into economic, environmental and social metrics.

Table 3.1 Description of Quantifiable Metrics

Metric/Subcomponents	**Description**
Operating & Maintenance Cost	This metric captures the financial expenditures related to the operation and upkeep of transportation infrastructure (highway, railroads, bike lanes) on a per passenger per trip basis. It includes costs for routine maintenance, repairs, and operational activities essential for the day-to-day functioning of transportation systems.
Emissions	This metric measures greenhouse gas emissions in terms of CO_2 equivalents per mile, providing a measure of the environmental impact of vehicle propulsion. It helps in understanding the contribution of different modes of transport to climate change.
Cost per Trip	This metric calculates the average cost associated with a single trip, encompassing expenses such as fares, fuel, and other related costs depending on mode. It provides insights into the economic efficiency and affordability of transportation options for users.
Active Travel (Walking/Cycling)	This metric assesses the extent of travel by walking or cycling, promoting health benefits and reducing environmental impact. It reflects the accessibility and safety of infrastructure that supports active transportation modes.
Variation in Delay Time	This metric tracks changes in delay times experienced during travel, highlighting variability and reliability issues in the transportation network. It is crucial for understanding the consistency and predictability of travel times.
Delay Time	This metric measures the total time delays experienced during travel, providing an indication of congestion levels and inefficiencies in the transportation system. It is critical for evaluating the impact of delays on overall travel time.
Injuries/Distance	This safety metric records the frequency of injuries per mile traveled. It is essential for assessing the safety performance of transportation systems and identifying areas that require safety improvements.
Loss of Life/Distance	This metric captures the incidence of fatalities per mile traveled, serving as a critical indicator of transportation safety. It helps in prioritizing safety interventions and policy measures to reduce fatalities.
Respiratory Effects/Distance	This health impact metric measures the respiratory effects of particulate matter (PM2.5) emissions per mile traveled. It highlights the health risks associated with air pollution from transportation and supports initiatives to improve air quality.

Table 3.2 Quantifiable cross-modal sustainability components

Dimension	Component	Subcomponent	Unit (per person per trip)
Economic: Impact to Agency	Direct Agency Cost	Operating & maintenance cost	$
Environmental: Impact to Environment	Emissions	GHG emissions	kg CO_2e
Social Impact to Traveler/Trip Taker	Travel cost	Cost per trip	$
	Health	Active travel(walking/cycling)	hour
	Reliability	Delay time	hour
	Reliability	Variation in delay time	hour
Social Impact to Other Humans	Safety	Injuries(number/mile)	number
	Safety	Loss of life per distance (number/mile)	number
	Public Health	Respiratory effects per distance (grams $PM_{2.5}$ e/mile)	g $PM_{2.5}$ e

Just because an impact is monetarily quantifiable, it does not mean that all dollars are equally important. For instance, $1,000 in health costs could be more important than $1,000 of delay costs depending on the individual and/or agency. Weighting of different components (or calculating the "utility") will be discussed Section 6 under sensitivity analysis.

3.2 Monetary Value of the Metrics

To make the metrics practical for decision-making, it is necessary to convert them into quantifiable cost values. Although this method enables comparability, it also assumes that different components are substitutable, which may not be always true. However, as one of the objectives of the study was to develop a holistic impact metric, aggregation was necessary. This section explains the methods used to convert each metric into a monetary value, considering both fixed and variable costs. The conversion process involves detailed calculations and assumptions, which are outlined to provide transparency and replicability. All the data sources described here can be found in Section 4.

Economic Dimension

For the *Direct Agency Cost* of vehicle (driving), the total annual expenditure is divided by the annual vehicle miles traveled (VMT) to get the impact per mile. It is then multiplied by the total distance of the trip. The occupancy for passenger vehicles was assumed to be 1.

For transit (bus, subway and commuter rail), the annual operating expenses are divided by the annual ridership, passenger miles traveled (PMT) for the impact per mile. Bus was a combination of bus and rapid bus for ridership and operating cost

To quantify the agency's cost for biking, a systematic approach was used. The process starts by comparing the construction costs of bike lanes to highways, calculating a ratio between them. This ratio is then used to estimate total bike infrastructure costs based on existing highway costs. To estimate biking miles, travel behavior data is analyzed to determine the percentage of people biking versus driving to work. Average speeds for biking and driving are assumed, allowing for an estimation of total annual Biking Miles Traveled (BMT).
The final calculations involve scaling the bike lane costs to the state level by applying the ratio of biking miles to highway miles.

This approach allows for a more accurate comparison of agency costs across different transportation modes, considering the relative usage and infrastructure needs of each mode. By using this method, planners and policymakers can better understand the economic implications of investing in bike infrastructure compared to other transportation options.

Environmental Dimension

Emissions: CO_2 emissions per mile of the various modes were multiplied by the trip distance to get the total emissions. The total impact for a trip was then multiplied by the cost of 1kg of CO_2 for the total cost. The CO_2 emissions per mile for each mode can be found in Section 4.

Social Dimension: Impact to the Trip Taker

Travel Cost: For driving, the average vehicle cost of a medium sedan per mile was used for the impact per mile, it was then multiplied by the trip distance to get the total impact per mile. The cost of parking was required for vehicles which was dependent on the case study location. For transit, MBTA fares (monthly pass and one way) were used. The fares were divided by 40 (20 working days but return to origin is assumed so 40) to get the cost per trip.) for regional trips. One-way trip fares are used for local and neighborhood trips (1–10 miles).
Health: Physical activity was computed with the active travel distance(miles) and multiplied by the infrastructure condition using the bikeability/walkability indices which scaled to be between 0 and 1. This value was then multiplied by the cost per mile for physical activity (active travel).
Reliability: quantified using the delay and variation of delay times of a mode multiplied by the value of time. Reliability for auto was calculated using Google Maps predicted time in traffic based on historical averages. These times are Best guess (default), Optimistic (best guess of short travel time from Google API) and Pessimistic (best guess of long travel time from Google API). For transit, the runtimes (RT) percentiles RT 10, 50 and 90 were used. For instance if Google Maps reports the travel time of a trip to be 55 minutes and it is usually between 45 minutes and 1 hour, then 55min is the Best guess, 45 minutes is the optimistic

time and 1 hour the Pessimistic time. Delay for vehicles was estimated by subtracting the Optimistic time of the trip from the Best guess to achieve the delay impact/mile. Variation of delay was by calculated by subtracting the Optimistic time from the Pessimistic time. For transit, delay was by subtracting RT10 from RT50. The variation of delay was by subtracting RT10 from RT90. The final values were then multiplied by the hourly value of time.

Social Dimension: Impact to Other Humans

Safety: The safety impact analysis focuses on quantifying the costs associated with physical harm caused by different modes of transportation, excluding property damage. For instance, in the case of driving, the analysis considered only crashes resulting in nonfatal physical injuries, which amounted to 30,581 out of a total of 133,158 crashes in 2022. The methodology involves calculating the impact per mile by dividing the total injuries or fatalities by the VMT for each mode of transportation. This impact per mile is then multiplied by the trip distance to determine the total impact per trip.

To establish a consistent injury cost, the analysis employs the KABCO value of life scale, which assigns monetary values to different types of injuries and fatalities. The process involves multiplying the percentage of each injury type occurring within a year by the corresponding KABCO costs. These values are then adjusted to the present value (2023) to obtain the cost per impact for both injuries and fatalities. The final step involves multiplying the total impact by the cost per impact to arrive at the total impact cost.

For example, in 2022, the distribution of crash types was analyzed, revealing that approximately 0.31% were fatal injury crashes, 1.89% were serious injury crashes, 13.07% were minor injury crashes, 7.92% were possible injury crashes, and 71.47% resulted in no injuries. By applying the KABCO scale to these percentages and adjusting for inflation, the injury cost was calculated to be approximately $96,630.40 in 2023 values. This comprehensive approach allows for a more accurate assessment of the safety implications associated with different transportation modes, providing valuable insights for policymakers and urban planners.

Public Health (PM2.5 exposure): For vehicles, the PM2.5 exposure for gasoline internal combustion engine vehicles (ICEV) was used to determine the impact per mile. Since the occupancy of vehicles was assumed to be one person per vehicle, there was no need for further division. PM2.5 emissions per trip (total impact) were calculated by multiplying the PM2.5 exposure by the trip distance. The total impact was then converted to tons and multiplied by the cost of PM2.5 per ton and adjusted to present value. For rail (subway and commuter), the average energy intensities per passenger mile were obtained. The mean fuel consumption was calculated by dividing the energy intensity by gallon of diesel fuel.

Then, PM2.5 emissions per passenger-mile were calculated by multiplying the fuel consumption rate by the PM2.5 weighted emission factor resulting in the impact per passenger-mile. The total PM2.5 emissions for a trip were calculated by multiplying the impact per passenger mile by the trip distance. The PM2.5 emissions per trip were then multiplied by the cost of PM2.5 per ton for the cost per trip. For buses, the average emission factor per passenger mile was used. This was divided by the average occupancy per bus to attain the impact per passenger mile. The PM2.5 emissions per trip (total impact) was then calculated by multiplying the PM2.5 impact per mile by the trip distance. The total impact was then converted to tons and multiplied by the cost of PM2.5 per ton and adjusted to present value.

3.3 Holistic Impact Measurement

The HIM was developed to provide an evaluation of the impacts of different transportation modes across trips. Although in monetary units, $1 in agency costs and $1 in user costs are equivalent, one may be more important depending on agency priorities. HIM converts various metrics into their weighed dollar equivalents to facilitate comparison and decision-making. It is important that these weights are selected through stakeholder engagement. In this study all weights were assumed to be one. The HIM could be calculated using

$$HIM = \sum_{i=1}^{N} W_i \times I_i \times C_i \tag{1}$$

where

- W_i = weight of metric obtained through stakeholder engagement (e.g., 1),
- I_i = impact of the metric i [e.g. kgCO_2/passenger mile × trip distance(miles)],
- C_i = monetary value of the metric i, and
- N = number of impacts (9 in this case, including all subcomponents).

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4.0 Data Collection and Case Studies

This section presents the data used in the development of this study in addition to specific case studies used in this study, illustrating the application of the developed metrics and methodologies.

4.1 Data Sources Used in the Study

Table 4.1 provides a summary of the impact per mile for various transportation modes, along with the sources of data used in these calculations and Table 4.2 provides the costs per impact for direct comparison. It is crucial to note that data availability and comparability varied across modes. For instance, when considering loss of life, only accidents directly caused by each mode were included (such as a car hitting a pedestrian or a bus colliding with a car, resulting in fatalities). However, some limitations exist in the data. Commuter rail statistics, for example, do not distinguish between different types of fatalities and include passenger deaths from various causes. This inconsistency made it impossible to draw direct comparisons for fatalities across all modes of transportation.

Table 4.1 Per-mile impact by transportation mode

Metric	**Mode**	**Impact/passenger mile**	**References**
Agency Cost	Car	\$0.072	(90,91)
	Commuter Rail	\$1.61	(92)
	Light Rail	\$2.72	(92)
	Heavy Rail	\$1.31	(92)
	Bus	\$3.11	(92)
	Biking	\$0.0082	(90,91,93–98)
Emissions	Car	0.404 $kgCO_2$	(99)
	Commuter Rail	0.15 $kgCO_2$	(100)
	Light Rail	0.16 $kgCO_2$	(100)
	Heavy Rail	0.10 $kgCO_2$	(100)
	Bus	0.29 $kgCO_2$	(100)
Travel Cost	Car	¢74/ \$0.748	(101)
	Transit	Trip dependent	(102)
	Biking	0	(94)

Metric	**Mode**	**Impact/passenger mile**	**References**
Active travel	All	Trip dependent	(103), *Google Maps*
Delay time	Car	Best guess - Optimistic time Value dependent on trip	*Google Maps*
	Transit	RT50 - RT10	(104,105)
Variation in delay time	Car	Pessimistic - Optimistic times	*Google Maps*
	Transit	RT90 - RT10	(104,105)
Injury/mile	Car	5.33E−07	(106,107) *Google Maps*
	Commuter Rail	Data not available	—
	Light Rail	1.3667E−06	(108)
	Heavy Rail	7.59E−07	(108)
	Bus	1.50E−06	(108)
Loss of life/mile	Car	7.18E−09	(106,107) *Google Maps*
	Commuter Rail	Data not available	—
	Transit (subway & bus)	0	(108)
PM2.5 equivalent/mile	Car	0.047 grams/ 5.18E−08 tons	(109), *Google Maps*
	Commuter Rail	0.039grams/ 4.30E−08 tons	(110,111), *Google Maps*
	Light Rail	0.032grams/3.53E−08 tons	(110,111)
	Heavy Rail	0.019grams/ 2.09E−08 tons	(110,111)
	Bus	0.0013grams/1.457E−09 tons	(109), *Google Maps*

Table 4.2 Metric cost per impact

Metric	Cost/impact	References
Cost of GHG per kg	$0.22	(112)
Value of time/hour	$30.26	(113)
Cost of active travel	$0.71	(66)
Injury cost	$96,630.40	(106,114)
Fatalities cost	$19,373,296	(114)
1 Ton of PM2.5	$516,914.26	(115)

All costs presented have adjusted to 2023 present value using Consumer Price Index (CPI) for the case study calculation and cost conversion. The data should be updated as more data is available. The following years of the data sources were used:

- 2022 crash data was used for safety.
- 2019 data for PM2.5 for subway and commuter rail.
- 2024 data for car PM2.5 and 2018 data for bus PM2.5.
- 2022 ridership data was used for all modes.
- 2021 Highway expenditure was used.
- 2022 transit operating expenditures were also used.

4.2 Case Studies

4.2.1 Description of Case Studies

To illustrate the application of the developed metrics three trip types were selected by the research team in conjunction with MassDOT and MBTA.
The trip types are

1. Regional trips (~30–60 miles, e.g., Attleboro to Boston or Worcester to Boston).
2. MBTA Core Service Area local trips (~5–10 miles, e.g., Quincy to Metropolitan Waterworks Museum).
3. Neighborhood trips (~1–3 miles, e.g., Franklin Park Zoo to The Museum of Bad Art).

A fourth local trip was added which compares two transit systems. (~1–6miles, e.g., Boston South Station to Fenway Park).

Regional Trip: Attleboro to Quincy Market

This case study examines a regional trip from Attleboro, a city in Bristol County, to Quincy Market, a historic market complex in downtown Boston. This trip is considered a regular work trip and return to origin is necessary as such monthly fares' passes are used in computing travel cost. The modes of transportation analyzed for this trip include:

- *Car:* Personal vehicle travel on highways and local roads for 38.9 miles.
- *Commuter Rail + Subway:* Using the MBTA Commuter Rail from Attleboro to South Station, followed by a short transit ride to Quincy Market for 32.09 miles. The transit ride could be the green line or orange line. Cost for both lines is shown in the holistic impact measurement workbook but the team worked with the orange line which had an overall lower cost.

Local Trip 1: Quincy Market to Metropolitan Waterworks Museum

This case study focuses on a local trip from Quincy Market to the Metropolitan Waterworks Museum, located in Chestnut Hill, Boston. This trip was not considered as a regular trip so one-way fares were used. The modes of transportation analyzed for this trip include:

- *Car:* Personal vehicle travel through city streets.
- *Subway:* Using the MBTA Green Line from Government Center Station to Reservoir Station, followed by a short walk.
- *Bike:* Cycling through urban bike lanes and shared paths.

This trip can be made with only light rail, bus and light rail or a combination of light and heavy rail. It mostly depends on maintenance along these lines.

Local Trip 2: Fenway Park to Boston South Station

This case study investigates a local trip from Fenway Park, Boston South Station, a major transportation hub. This trip was to compare two transit modes. The modes of transportation analyzed for this trip include:

- *Car:* Personal vehicle travel through city streets with a distance of 3.3 miles.
- *Commuter Rail:* Walking to the MBTA Commuter Rail at Lansdowne Station, traveling to South Station, and then walking to the destination with distance of 2.56 miles.
- *Light Rail:* Using the MBTA Green Line from Kenmore Station to Boylston Station followed by a short walk to South Station with a distance of 1.65 miles.
- *Bike:* Cycling through urban bike lanes and shared paths.

Neighborhood Trip: Franklin Park Zoo to The Museum of Bad Art (2.3 miles)

This case study explores a neighborhood trip from Franklin Park Zoo, a large zoo in Boston, to The Museum of Bad Art, also located in Boston. The modes of transportation analyzed for this trip include:

- *Car:* Personal vehicle travel through local roads.
- *Bus:* Local bus services connecting the two locations.
- *Bike:* Cycling through neighborhood bike lanes and shared paths.

4.2.2 Case Study Results

This section presents the final costs for each case study. The detailed calculations can be found in the appendix. The results are organized by the dimensions of impact: economic, environmental, and social. Tables 4.3 through 4.6 summarize the impacts for different modes of transportation, providing a comprehensive comparison.

Table 4.3 presents a comparative analysis of costs across different transportation modes for a regional trip. The data reveals significant variations in direct agency costs, with commuter rail and heavy rail showing substantially higher expenses compared to driving. This disparity is attributed to the extensive infrastructure requirements and lower ridership associated with public transit systems. In terms of environmental impact, driving generates higher emissions costs along the route, reflecting the greater GHG footprint of personal vehicles. Also, when considering travel costs, driving incurs a much higher expense per trip, primarily due to fuel, insurance, maintenance, parking costs while public transit emerges as a more economical alternative. Interestingly, commuter rail and heavy rail offer health benefits, represented by negative values in the analysis, due to the physical activity involved in walking to and from stations—an advantage not present in driving. Public transit also demonstrates better reliability metrics compared to personal vehicles. Moreover, public transportation shows lower costs associated with injuries and respiratory effects, underscoring its safer and cleaner nature. In conclusion, the human impact measure or total cost is lower for the combination of commuter rail and heavy rail compared to driving, indicating that public transit represents a more sustainable and cost-effective transportation mode for this type of regional trip

Table 4.3 Regional Trip Cost Breakdown

Dimension	**Component**	**Metric**	**Driving**	**C Rail + H Rail**
Economic (Impact to Agency)	Direct Agency Cost	Adjusted total cost	\$2.80	\$51.25
Environmental (Impact to Environment)	Emissions	Emissions along route	\$3.51	\$1.04
Internal Social: Impact to Humans	Travel Cost	Cost per trip	\$44.01	\$9.00
	Health	Active Travel-Physical Activity	\$0.00	−\$0.46
	Reliability	Delay time	\$5.04	\$1.76
	Reliability	Variation in delay time	\$12.62	\$4.24
External Social: Impact to Humans	Safety	Injury/mile	\$2.00	\$0.10
	Safety	loss of life per distance	\$5.40	N/A
	Public Health	Respiratory effects	\$1.04	\$0.70
HIM/Total Cost	—	—	\$76.51	\$67.43

Table 4.4 illustrates the cost differences across transportation modes for local trip 1. Light rail demonstrates a significantly higher agency cost due to its infrastructure and operational requirements, while driving exhibits lower direct agency costs, attributed to high VMT and the current rarity of new road construction. In terms of environmental impact, driving incurs higher emissions costs compared to light rail, reflecting the greater ecological footprint of personal vehicles. When considering travel expenses, driving proves to be considerably more costly per trip, with light rail emerging as a more economical alternative. Light rail also shows advantages in health metrics due to increased active travel and demonstrates superior reliability compared to driving. In terms of safety and respiratory effects, light rail presents higher injury costs but no loss of life cost, coupled with lower respiratory effects costs

compared to driving. Overall, the HIM is lower for light rail compared to driving, indicating that it represents a more sustainable and cost-effective transportation mode for this local trip.

Table 4.4 Local trip 1 cost breakdown

Dimension	**Component**	**Metric**	**Driving**	**Light Rail**	**Biking**
Economic (Impact to Agency)	Direct Agency Cost	Adjusted total cost ($)	\$0.45	\$16.07	\$0.05
Environmental (Impact to Environment)	Emissions	Emissions along route (kg CO_2)	\$0.57	\$0.22	\$0.00
Internal Social: Impact to Humans	Travel Cost	Cost per trip ($)	\$24.71	\$2.40	\$0.00
	Health	Active Travel-Physical Activity + Infrastructure condition	\$0.00	−\$0.36	−\$3.17
	Reliability	Delay time (min)	\$3.03	\$2.39	\$0.00
	Reliability	Variation in delay time (min)	\$7.57	\$5.14	\$0.00
External Social: Impact to Humans	Safety	Injury/mile	\$0.32	\$0.81	\$0.00
	Safety	loss of life per distance	\$0.87	\$0.00	\$0.00
	Public Health	Respiratory effects ($PM_{2.5}$/mile)	\$0.17	\$0.11	\$0.00
HIM/ Total Cost	—	—	\$37.69	\$26.77	−\$3.12

Table 4.5 presents a comparison of cost differences across various transportation modes for local trip 2, focusing on different forms of public transportation. In terms of direct agency costs, biking emerges as the most economical option due to minimal infrastructure and operational expenses, while commuter rail and light rail incur higher costs reflecting their substantial infrastructure and operational requirements. Regarding emissions, driving produces the highest environmental cost, with biking generating no emissions, and public transit modes (commuter rail and light rail) falling between these extremes. Travel costs follow a similar pattern, with driving being the most expensive, biking incurring no direct travel costs, and public transit modes offering economical alternatives. Both biking and public transit demonstrate health benefits, represented by negative values in the analysis, due

to the physical activity involved, while driving does not offer this advantage. Additionally, biking and public transit show better reliability metrics compared to driving. In terms of safety and respiratory effects, biking stands out with no associated costs for injuries, fatalities, or respiratory effects. Public transit modes also perform well in this category, showing lower costs compared to driving and thus presenting themselves as safer and cleaner alternatives. Overall, the HIM is the lowest for biking, indicating it as the most sustainable mode for this trip, followed in order by commuter rail, light rail, and driving.

Table 4.5 Local trip 2 cost breakdown

Dimension	Component	Metric	Driving	Biking	C Rail	L Rail
Economic (Impact to Agency)	Direct Agency Cost	Adjusted total cost ($)	\$0.24	\$0.02	\$4.10	\$4.49
Environmental (Impact to Environment)	Emissions	Emissions along route (kg CO_2)	\$0.30	\$0.00	\$0.09	\$0.06
Internal Social: Impact to Humans	Travel Cost	Cost per trip ($)	\$22.47	\$0.00	\$2.40	\$2.40
	Health	Active Travel-Physical Activity + Infrastructure condition	\$0.00	−\$1.51	−\$0.13	−\$0.56
	Reliability	Delay time (min)	\$3.03	\$0.00	N/A	\$1.97
	Reliability	Variation in delay time (min)	\$8.17	\$0.00	N/A	\$4.24
External Social: Impact to Humans	Safety	Injury/mile	\$0.17	\$0.00	N/A	\$0.23
	Safety	loss of life per distance	\$0.46	\$0.00	N/A	\$0.00
	Public Health	Respiratory effects ($PM_{2.5}$/mile)	\$0.09	\$0.00	\$0.06	\$0.03
HIM/Total Cost	—	—	\$34.92	−\$1.49	\$6.51	\$12.84

Table 4.6 illustrates the cost differences across various transportation modes for a Neighborhood trip. In terms of direct agency costs, biking emerges as the most economical option, while the bus incurs higher costs due to its operational expenses. The environmental impact varies significantly among the modes, with driving generating the highest emissions cost, followed by the bus, while biking produces no emissions. Travel costs follow a similar pattern, with driving being the most expensive, biking incurring no direct travel costs, and the bus offering an economical alternative to driving. Health and reliability metrics favor biking, which shows a significant health benefit due to physical activity and demonstrates the best reliability. The bus also offers health benefits and good reliability, ranking second in these categories, while driving provides no health benefits. Regarding safety and respiratory effects, biking stands out with no associated costs for injuries, fatalities, or respiratory

effects. The bus performs better than driving in this category, presenting itself as a safer and cleaner alternative. Overall, the HIM or Total Cost is lowest for biking, indicating it as the most sustainable mode for this neighborhood trip, followed by the bus and then driving.

Table 4.6 Neighborhood trip cost breakdown

Dimension	Component	Metric	Driving	Biking	Bus
Economic (Impact to Agency)	Direct Agency Cost	Adjusted total cost ($)	$0.17	$0.02	$7.16
Environmental (Impact to Environment)	Emissions	Emissions along route (kg CO_2)	$0.21	$0.00	$0.15
Internal Social: Impact to Humans	Travel Cost	Cost per trip ($)	$26.72	$0.00	$1.70
	Health	Active Travel-Physical Activity + Infrastructure condition	$0.00	−$1.06	−$1.62
	Reliability	Delay time (min)	$3.63	$0.00	$2.15
	Reliability	Variation in delay time (min)	$6.66	$0.00	$14.47
External Social: Impact to Humans	Safety	Injury/mile	$0.12	$0.00	$0.35
	Safety	loss of life per distance	$0.32	$0.00	$0.00
	Public Health	Respiratory effects ($PM_{2.5}$/mile)	$0.06	$0.00	$0.009
HIM	—	—	$37.89	−$1.04	$24.35

These results highlight the relative sustainability of different transportation modes. For instance, biking consistently shows lower costs and emissions but requires significant active travel. Conversely, driving tends to have higher costs and emissions, reflecting its environmental and economic impact. Public transit options, such as commuter rail and light rail, offer a balance between cost and emissions, making them a viable sustainable alternative.

5.0 Sensitivity Analysis

Sensitivity analysis is a crucial part of this study as it evaluates how variations in key parameters affect the overall outcomes. This section focuses on two primary types of sensitivity analysis: weight sensitivity analysis and scenario sensitivity analysis.

The sensitivity analysis provides valuable insights for future decisions, investment plans, and actions. By identifying the parameters that most significantly impact the HIM, policymakers and planners can prioritize areas for improvement and allocate resources more effectively. This ensures that future investments are directed toward initiatives that offer the greatest potential for enhancing sustainability.

5.1 Weight Sensitivity Analysis

Weight sensitivity analysis examines how different weights assigned to various components by stakeholders influence the final cost metrics. This analysis helps understand the importance of each component and how stakeholder priorities can impact decision-making. Table 5.1 illustrates the weights of components according two individual stakeholders. To ensure that the results are comparable to unweighted case, weights were normalized to ensure that their total would still be 9, equal to the unweighted scenario where all weights were equal to 1. For the components with two impacts, it was assumed that the subcomponents share equal weight. In this case, stakeholder 1 placed higher importance on emissions and health where stakeholder 2 placed higher importance on agency cost and safety

Table 5.1 Stakeholder weights

Components	Stakeholder 1	Stakeholder 2
Direct agency cost	0.45	1.35
Emissions	1.8	1.08
Travel cost	0.9	1.26
Active travel	1.8	0.45
Delay time	0.675	0.585
Variation in delay time	0.675	0.585
Injuries	0.675	1.35
Fatalities	0.675	1.35
Public health	1.35	0.99
Total	9	9

Table 5.2 shows the change in the final HIM of the regional trip when weights are applied for each stakeholder. Due to different preferences of stakeholders, HIM for stakeholder 1 significantly opens the gap between driving and public transportation, whereas the HIM for stakeholder 2 narrows this gap due to higher importance of agency cost. This analysis clearly illustrates the importance of stakeholder engagement and determining weights based on agency priorities.

Table 5.3 and Table 5.4 show the difference in the final HIM for the local trip 1 and the neighborhood trip, respectively. They show similar trends for the final metric value depending on stakeholder preference. In all cases, driving is still the mode with the highest cost. However, the actions may target different components of sustainability depending on stakeholder preference.

These case studies further show the importance of stakeholder engagement and differences in following targeted actions to reduce the final cost. Possible actions may include promoting active and or public transportation, environmental sustainability initiatives including emission reduction and safety enhancements depending on the weights of the components.

Table 5.2 Unweighted versus weighted regional trip cost

Metric	**Unweighted**[1]		**Stakeholder 1**[2]		**Stakeholder 2**[3]	
	Driving	**C Rail + H Rail**	**Driving**	**C Rail + H Rail**	**Driving**	**C Rail + H Rail**
Adjusted agency cost ($)	$2.80	$51.04	$1.26	$22.97	$3.78	$68.90
Emissions along route (kg CO_2)	$3.51	$1.06	$6.31	$1.91	$3.79	$1.14
Cost per trip ($)	$44.10	$9.00	$39.69	$8.10	$55.56	$11.34
Active travel	$0.00	−$0.46	$0.00	−$0.82	$0.00	−$0.21
Delay time (min)	$5.04	$1.76	$3.41	$1.18	$2.95	$1.03
Variation in delay time (min)	$12.62	$4.24	$8.52	$2.86	$7.38	$2.48
Injury/mile	$2.00	$0.10	$1.35	$0.07	$2.70	$0.14
Loss of life per distance	$5.40	$0.00	$3.65	$0.00	$7.29	$0
Respiratory effects ($PM_{2.5}$/mile)	$1.04	$0.69	$1.40	$0.94	$1.03	$0.68
HIM	$76.51	$67.42	$65.59	$37.21	$84.49	$85.50

[1] Shows the unweighted cost of impacts for a regional trip.

[2] Shows the cost of weighted impacts based on stakeholder 1 preference.

[3] Shows the cost of weighted impacts based on stakeholder 2 preference.

Table 5.3 Unweighted versus weighted local trip 1

Metric	**Unweighted**			**Stakeholder 1**			**Stakeholder 2**		
	Driving	**Light Rail**	**Biking**	**Driving**	**Light Rail**	**Biking**	**Driving**	**Light Rail**	**Biking**
Adjusted agency cost ($)	$0.45	$18.54	$0.05	$0.20	$7.23	$0.02	$0.61	$21.69	$0.07
Emissions along route (kg CO_2)	$0.57	$0.25	$0.00	$1.02	$0.39	$0.00	$0.61	$0.23	$0.00
Cost per trip ($)	$24.71	$2.40	$0.00	$22.24	$2.16	$0.00	$31.14	$3.02	$0.00
Active travel	$0.00	−$0.36	−$3.17	$0.00	−$0.65	−$5.70	$0.00	−$0.16	−$1.43
Delay time (min)	$3.03	$2.39	$0.00	$2.04	$1.61	$0.00	$1.77	$1.40	$0.00
Variation in delay time (min)	$7.57	$5.14	$0.00	$5.11	$3.47	$0.00	$4.43	$3.01	$0.00
Injury/mile	$0.32	$0.94	$0.00	$0.22	$0.55	$0.00	$0.44	$1.09	$0.00
Loss of life per distance	$0.87	$0.00	$0.00	$0.59	$0.00	$0.00	$1.18	$0.00	$0.00
Respiratory effects ($PM_{2.5}$/mile)	$0.17	$0.12	$0.00	$0.23	$0.14	$0.00	$0.17	$0.11	$0.00
	$37.69	$26.77	−$3.12	$31.65	$14.90	−$5.68	$40.34	$30.39	−$1.36

Table 5.4 Unweighted versus weighted neighborhood trip

Metric	**Unweighted**			**Stakeholder 1**			**Stakeholder 2**		
	Driving	**Biking**	**Bus**	**Driving**	**Biking**	**Bus**	**Driving**	**Biking**	**Bus**
Adjusted total cost ($)	$0.17	$0.02	$7.16	$0.07	$0.01	$3.22	$0.22	$0.03	$9.66
Emissions along route (kg CO_2)	$0.21	$0.00	$0.15	$0.37	$0.00	$0.27	$0.22	$0.00	$0.16
Cost per trip ($)	$26.72	$0.00	$1.70	$24.05	$0.00	$1.53	$33.67	$0.00	$2.14
Active travel	$0.00	−$1.06	−$1.62	$0.00	−$1.90	−$2.91	$0.00	−$0.48	−$0.73
Delay time (min)	$3.63	$0.00	$2.15	$2.45	$0.00	$1.45	$2.12	$0.00	$1.26
Variation in delay time (min)	$6.66	$0.00	$14.47	$4.49	$0.00	$9.76	$3.89	$0.00	$8.46
Injury/mile	$0.12	$0.00	$0.35	$0.08	$0.00	$0.23	$0.16	$0.00	$0.47
Loss of life per distance	$0.32	$0.00	$0.00	$0.22	$0.00	$0.00	$0.43	$0.00	$0.00
Respiratory effects ($PM_{2.5}$/mile)	$0.06	$0.00	$0.01	$0.08	$0.00	$0.01	$0.06	$0.00	$0.01
—	$37.89	−$1.04	$24.35	$31.82	−$1.89	$13.56	$40.79	−$0.45	$21.43

5.2 Scenario Sensitivity Analysis

The scenario sensitivity analysis aims to explore how changes in input values influence the final cost metrics of various transportation modes. This analysis helps policy makers understand the potential impacts of different future scenarios and make informed decisions that promote sustainability and efficiency. This analysis helps assess the robustness of the HIM framework under different policy scenarios.

The scenario sensitivity Analysis involves systematically varying key input values and observing the resulting changes in the final cost metrics. The key inputs considered in this analysis include:

1. **Ridership (PMT)**: Changes in ridership levels influence agency costs, particularly for public transit modes, by spreading costs over a larger or smaller number of passengers.
2. **Emission Rates**: Adjusting emission rates allows us to understand the impact of stricter or more lenient environmental regulations on transportation costs.

The following sections present the sensitivity of final cost metrics to changes in key input values for various transportation modes: driving, biking, bus, light rail, and commuter rail.

Change in Ridership or Usage

Figure 5.1 illustrates the sensitivity of total costs for transit to changes in PMT and how it affects agency cost for the regional trip. The percentage changes in PMT are plotted against the corresponding total costs. The figure shows that as PMT increases, the agency cost per passenger mile decreases significantly. This is due to the costs of transit operations being spread over a larger number of passengers, thereby reducing the per-passenger cost. Conversely, a decrease in PMT leads to higher costs per passenger. This underscores the importance of maintaining or increasing ridership levels to optimize the financial efficiency of transit systems.

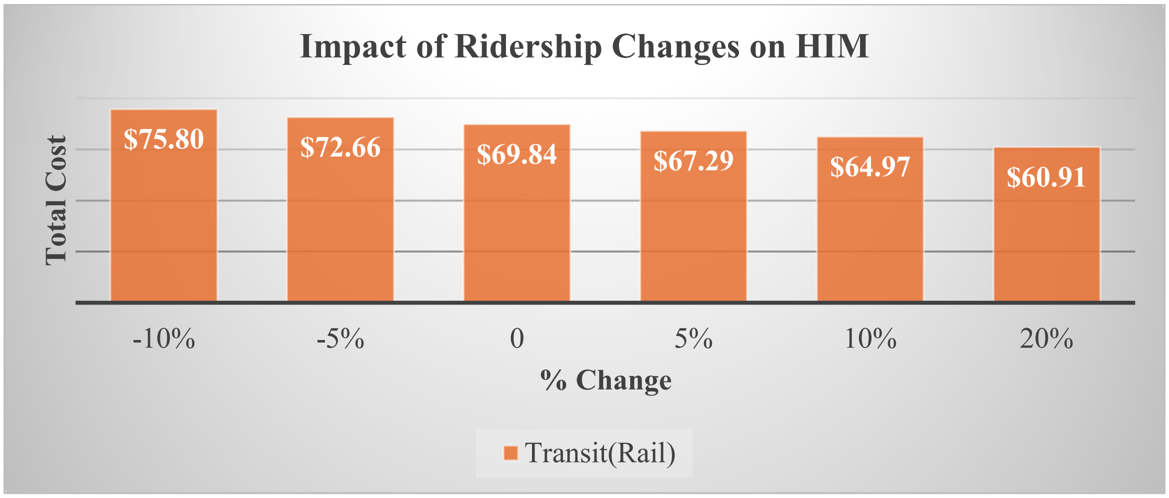

Figure 5.1 Effect of PMT on cost for the regional trip

Figure 5.2 shows how changes in ridership (or use) percentages impact the total costs for different modes (biking, light rail, and commuter rail) for local trip 2. The costs are shown for different percentage changes in ridership. The results indicate that for light rail and commuter rail, increases in ridership significantly reduce the agency cost and hence lower the total cost per passenger. Biking, with its initially low cost, shows minimal sensitivity to ridership changes.

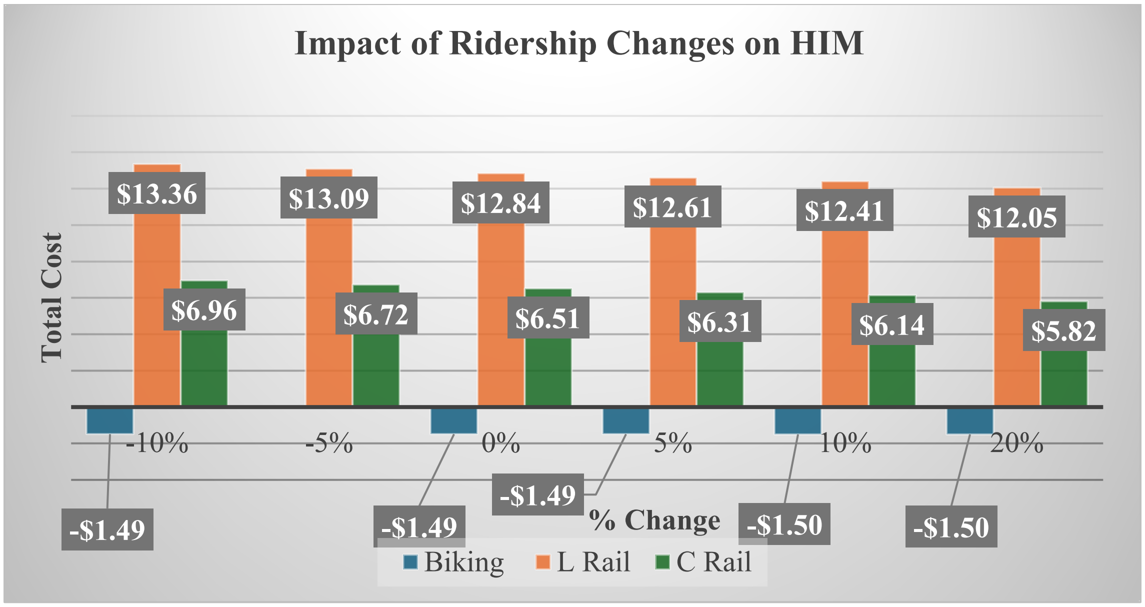

Figure 5.2 Effect of PMT on cost for local trip 2

Figure 5.3 illustrates the effect of changes in PMT on the total cost on a neighborhood trip, comparing Biking and Bus. As with previous figures, increased PMT results in lower total costs per passenger for the Bus mode. Biking costs remain consistently low and are not significantly affected by changes in PMT. Similar to the findings in local trip 2, increased PMT for buses leads to reduced costs per passenger, highlighting the economic advantages of higher ridership. Biking continues to be a highly cost-effective mode of transportation. Policies aimed at increasing bus ridership can help reduce overall transportation costs.

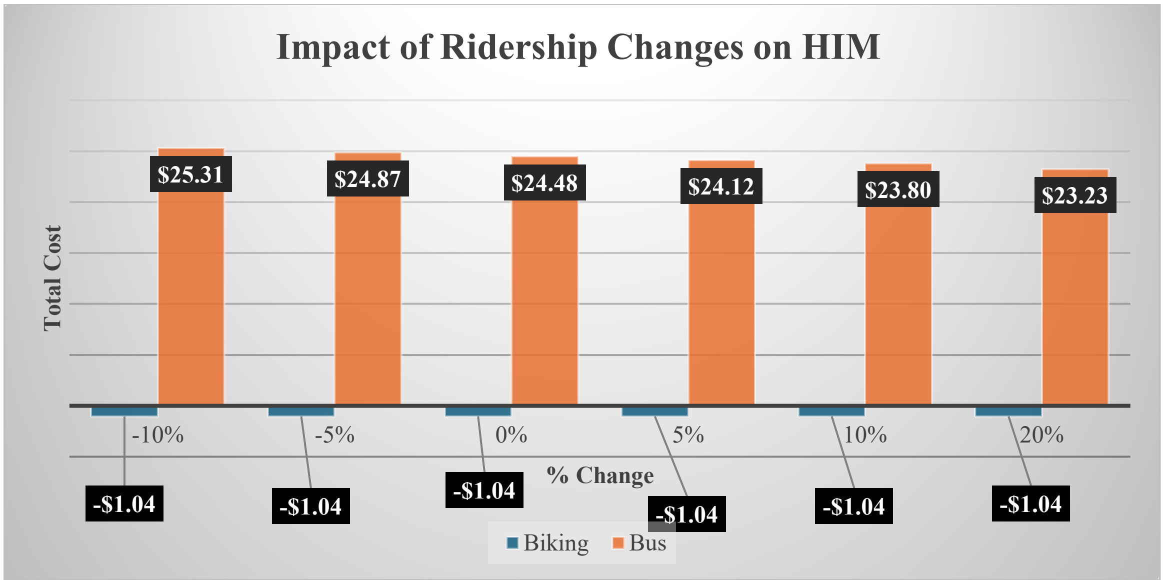

Figure 5.3 PMT change on neighborhood cost

Emission Reduction

Figure 5.4 illustrates the sensitivity of total costs for a regional trip to changes in vehicle emission types, specifically comparing gasoline and hybrid vehicles. The total costs are plotted for each vehicle type. The figure shows that using hybrid vehicles results in lower total costs compared to gasoline vehicles. This reduction is primarily due to the lower emission rates and improved fuel efficiency of hybrid vehicles. However, while the user cost is reduced, the overall cost remains relatively unchanged due to high costs of other components.

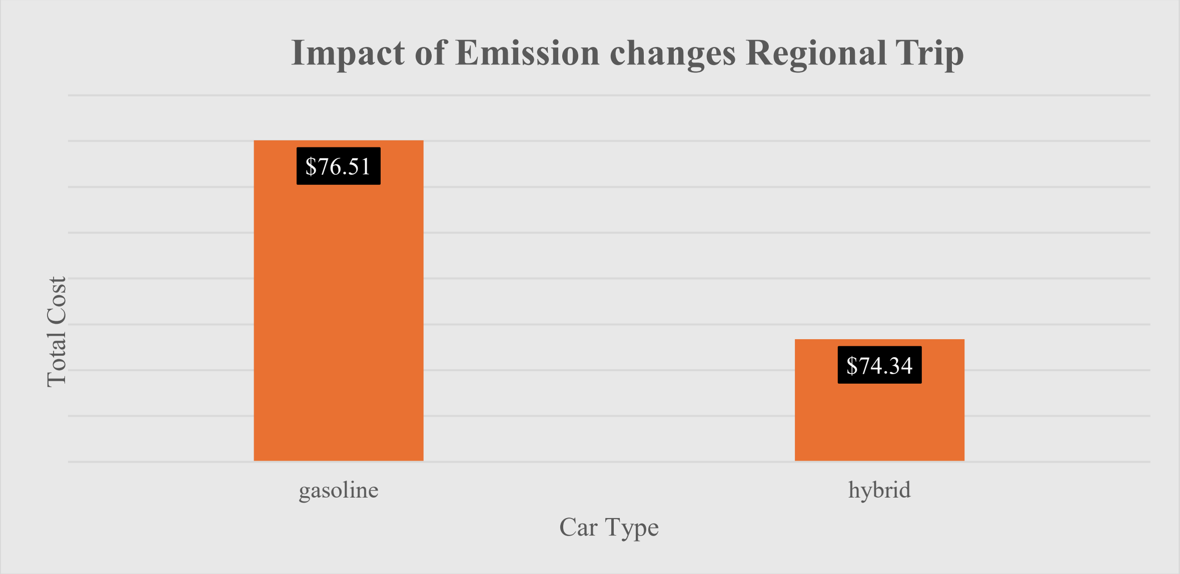

Figure 5.4 Engine type on regional cost

The overall effect of vehicle type on other trips is even lower for other trips due to the short distance of the trip. This is because the other components have higher costs, especially for shorter trips. However, it is important to note that this metric only shows the total cost of travel from point A to B on a per-passenger basis. Because there are many more people traveling via driving, the overall impact on reducing tailpipe emissions and environmental sustainability is still quite significant and should not be ignored. Moreover, although one of the objectives of the project was to quantify sustainability using one number, conversion of any component, including emissions may over or underestimate the actual significance of a component due to errors in conversion to monetary value.

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6.0 Limitations and Assumptions

This section outlines the limitations and assumptions inherent in the methodology and calculations of the cost metrics used in this study. Understanding these limitations and assumptions is crucial for interpreting the results accurately and recognizing the potential areas for future improvement.

6.1 Assumptions

General Assumptions

1. This project focuses on a snapshot of the current state of infrastructure. It does not consider any time history or future projections.
2. All impacts, including costs, were translated into impact per passenger mile to ensure comparability across different modes of transportation.
3. Assumed that all trips were taken during the peak morning hour (9 AM).
4. The shortest travel time was used across trip case studies.

Economic Component Assumptions

1. In this study, it was assumed that agency costs for highways, public transportation (subway, commuter rail) and biking infrastructure primarily include operation and maintenance expenses. This assumption is based on the observation that while public transportation and biking infrastructure are experiencing significant expansions, most highway investments focus predominantly on operation and maintenance rather than expansion. Consequently, to ensure a fair comparison across different transportation modes, capital investments and the costs associated with expanding existing infrastructure are excluded from the economic analysis. This approach aims to prevent any potential disadvantage to expanding modes of transportation due to the inherent differences in their developmental stages and funding allocations.
2. Different data sources were used to compile the economic costs associated with each mode of transportation. This diversity in sources can potentially affect the accuracy and comparability of the economic evaluations presented. To mitigate these concerns and enhance the reliability of future studies, the standardization of economic data reporting is recommended. Such standardization would aid in achieving more consistent and comparable economic assessments across transportation modes.

Environmental Component Assumptions

1. The analysis used US averages of emissions for all modes of transportation. This helps in providing a generalized view applicable to the region.
2. It was assumed that CO_2 emissions would follow a similar trend as other emissions (such as NOx, PM10). Thus, CO_2 was used as a proxy for estimating the overall environmental impact. Moreover, CO_2 emissions are the highest contributor to GHG.
3. The study focused solely on emissions during the operational (use) stage of vehicles. Other life-cycle stages such as manufacturing, maintenance, and end of life were not considered.

4. Emissions quantified in the study were exclusively from tailpipe emissions.
5. For passenger vehicles, it was assumed that the primary fuel type was gasoline. For buses and other public transportation modes, diesel was assumed to be the primary fuel.
6. Study assumed a medium sedan light-duty gasoline vehicle for all trips to standardize calculations across various scenarios.

Social Component Assumptions

1. Cost components considered for driving cost included fuel, insurance, maintenance, depreciation costs. The study excluded the cost of purchasing a vehicle.
2. For regional trips, monthly pass fares are divided by 40 (assuming 20 working days with a return trip each day) to determine the cost per trip. For local and neighborhood trips (1–10 miles), one-way trip fares were used.
3. The average operating and maintenance cost for biking was estimated to be approximately $50 per year. This was considered negligible, and thus set to zero dollars.
4. It was assumed that best guess travel time is comparable with RT50 (median travel time), the optimistic travel time is comparable with RT10 (10th percentile travel time), and the pessimistic travel time is comparable with RT90 (90th percentile travel time).
5. Active travel (biking and walking) was calculated as a weighted summation of travel time and bikeability and walkability scores. This incorporates both the physical effort and infrastructure condition into the cost-benefit analysis.
6. Zero delay and variation of delay for biking was assumed to simplify the analysis of non-motorized modes.
7. Quantified public health impacts based on PM2.5 levels due to data availability and its well-established correlation with health outcomes.
8. PM calculations assumed that PM2.5 emissions were primarily from combustion, due to lack of data regarding other sources of PM.
9. Maximum average load bus occupancy was used to estimate PM2.5 emissions, ensuring a representative analysis of bus emissions.

6.2 Limitations

Despite the rigorous methodologies employed in this study, there are inherent limitations that must be acknowledged. These limitations highlight the constraints in the methodology. Recognizing these limitations is essential for contextualizing the results and identifying areas where further research and data collection are needed to enhance the robustness of the findings. These limitations are the following:

1. The lack of standardized economic data reporting across different modes of transportation can affect the accuracy and reliability of cost comparisons.
2. Using US averages may not capture regional variations in emissions and environmental impacts.
3. The study relies on data from various sources, which may have different collection

methodologies, time periods and reporting standards. This can introduce variability and affect the comparability of results.

4. Commuter rail had no reliability or injury data that could be used to compare to other modes. In addition, fatality data did not distinguish between fatalities caused by the mode and fatalities happened on the mode.

Recognizing these assumptions are limitations are crucial in the use and understanding of HIM. Changes in data sources, weights and life-cycle boundaries may change the result. As stated, HIM aims to measure impacts on a per passenger per trip basis. Therefore, it should be only used to compare two different modes when travel between a specific point A and B is considered. It should not be used to make general assumptions and draw conclusions about the overall sustainability of a mode. Finally, HIM is best used when at least two mode alternatives exist. Mode specific sustainability metrics should be developed to evaluate different routes within the same mode and may allow for the inclusion of more sustainability factors.

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7.0 Conclusions and Future Research

This study developed a methodology for assessing and comparing the sustainability of different transportation modes on a per-trip basis. The key objectives were to define relevant sustainability impacts across economic, environmental and social dimensions; quantify these impacts for different transportation modes on a per-passenger, per-trip basis; convert impacts to monetary costs/gains; develop a holistic impact measurement methodology to aggregate impacts; and perform sensitivity analysis on the results. The methodology involved literature review and stakeholder engagement to identify key sustainability metrics, data collection from various transportation databases and previous studies, development of quantifiable cross-modal metrics covering economic, environmental and social impacts, conversion of metrics to monetary values, application of the methodology to case studies of regional, local and neighborhood trips in Massachusetts, and sensitivity analysis on stakeholder weightings and future scenarios.

Key findings from the case studies revealed that public transit and active transportation generally showed lower agency costs and emissions compared to private vehicles, especially for shorter trips. Cars often provided the shortest travel times but incurred higher social costs due to safety risks and health impacts. When all factors were considered holistically, public transit and bicycling frequently emerged as the most sustainable options, particularly for shorter trips.

7.1 Conclusions

The study developed a cross-modal sustainability assessment methodology that provides a holistic view of transportation sustainability impacts and enables direct comparison between different modes on a per-trip basis. The methodology converts diverse impacts into monetary values for easier decision-making and is flexible, allowing for tailoring through stakeholder weightings.

The results highlight the importance of considering multiple sustainability factors beyond just financial costs or travel times. For example, in the regional trip case study from Attleboro to Quincy Market, while the direct agency cost for commuter rail and heavy rail ($51.25) was significantly higher than driving ($2.80), the total cost including environmental and social impacts was lower for public transit ($67.43) compared to driving ($76.51). This demonstrates the potential sustainability benefits of public transportation for longer trips.

For shorter trips, active transportation often emerged as the most sustainable option. In the neighborhood trip case study from Franklin Park Zoo to The Museum of Bad Art, biking showed a negative total cost (−$1.04) due to health benefits, compared to driving ($37.89) and bus ($24.35), illustrating the significant sustainability advantages of active transportation for short urban trips.

However, the study also revealed several limitations. The lack of standardized economic data reporting across different modes of transportation affected the accuracy and reliability of cost comparisons. Using US averages for emissions data may not have captured regional variations in environmental impacts. The reliance on data from various sources with different collection methodologies, time periods, and reporting standards introduced variability and affected the comparability of results.

Additionally, certain assumptions were made that could impact the results. For instance, the study focused on a snapshot of the current state of infrastructure without considering time history or future projections. All impacts were translated into impact per passenger mile, which may not fully capture the nuances of different transportation modes. The analysis also assumed all trips were taken during the peak morning hour, which may not represent the full range of travel patterns.

7.2 Future Research Needs

Future research should focus on addressing the limitations and assumptions identified in this study. Efforts should be made to develop standardized methodologies for data collection and reporting across different transportation modes. This would improve the accuracy and comparability of sustainability assessments.

Expanding the scope of the analysis to include a broader range of environmental impacts beyond just CO_2 emissions would provide a more comprehensive assessment of environmental sustainability. Future studies should also consider incorporating the full life cycle of transportation modes, including manufacturing, maintenance, and end-of-life stages, rather than focusing solely on operational impacts.

Research is needed to develop more nuanced models that can account for variations in travel patterns, including off-peak travel and seasonal variations. This would provide a more accurate representation of the sustainability impacts of different transportation modes across various scenarios.

Efforts should be made to improve data collection for newer and emerging transportation modes, as well as for specific metrics where data was lacking in this study, such as reliability and injury data for commuter rail.

Future research could also explore the integration of this sustainability assessment methodology with interactive mapping tools and Geographic Information Systems (GIS). This integration could enable the creation of dynamic, visual representations of sustainability impacts across different transportation networks. Such tools could allow planners and policymakers to visualize how changes in transportation infrastructure or policies might affect sustainability outcomes in real-time.

The development of user-friendly interfaces that incorporate this methodology could facilitate its use in practical decision-making processes. These interfaces could allow stakeholders to adjust weightings, explore different scenarios, and visualize the impacts of various transportation choices on a map-based platform.

Finally, longitudinal studies should be conducted to assess how sustainability impacts change over time, particularly in response to policy interventions or infrastructure investments. This would provide valuable insights into the long-term effectiveness of different strategies for improving transportation sustainability.

By addressing these areas, future research can build on the foundation laid by this study to create more comprehensive, accurate, and practically applicable tools for assessing and improving the sustainability of transportation systems.

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Appendix

Trip Calculation Details

Table A.1 2022 Totals for MBTA

Travel Type	Type	Unlinked Passenger Trips	Passenger Miles	Operating Expenses	Average Cost per Trip	Average Fares per Trip
Bus	DO	66,787,609	168,662,733	$514,500,114	$7.70	$0.83
Bus	PT	2,369,255	5,307,131	$17,841,007	$7.53	$0.05
Bus Rapid Transit	DO	7,433,990	16,605,586	$40,324,535	$5.42	$0.81
Commuter Rail	PT	14,310,785	307,334,036	$474,347,246	$33.15	$5.64
Demand Response	PT	930,174	7,518,032	$99,595,993	$107.07	$2.92
Ferryboat	PT	595,180	4,375,835	$14,935,167	$25.09	$7.24
Heavy Rail	DO	78,861,897	266,054,405	$333,756,435	$4.23	$1.59
Light Rail	DO	31,261,416	76,107,994	$199,157,007	$6.37	$1.51
Trolleybus	DO	905,096	2,123,790	$18,370,594	$20.30	$1.18

Table A.2 Crash Cost by Severity

Crash Severity	Crash Severity Defined	2019 Recommended Comprehensive Crash Unit Costs
K	Crashes involving a Fatal Injury	$16,257,800
A	Crashes involving a Serious Injury	$941,300
B	Crashes involving a Non-serious Injury	$284,600
C	Crashes involving a Possible Injury	$179,600
O	Crashes involving No Injuries	$16,700
KA	Crashes involving a Fatal Injury OR a Serious Injury	$2,764,700
KAB	Crashes involving a Fatal Injury OR a Serious Injury OR a Non-Serious Injury	$706,100
KABC	Crashes involving a Fatal Injury OR an Injury of any type	$441,000

Regional Trip

Trip Details:

- Route: Attleboro Arts Museum to Quincy Market
- Time: Peak AM
- Distance: 38.9 miles by car, 32.09 miles by transit
- Mode: driving and public transit

Economic Dimension

Direct Agency Cost

Mode 1*:* Auto (Drive Alone)

Operating cost = $3,654,925,000(2021) ~$4,109,794,802(2023)

VMT = 56,949,000,000

Impact/mile = $\frac{Operating\ cost}{VMT} = \frac{\$4{,}109{,}794{,}802}{56{,}949{,}000{,}000}$ = $0.072

Impact/trip = cost/mile × trip distance

= $0.072 × 38.9 miles

- Agency cost/trip = $2.80

Mode 2: Commuter Rail + Heavy Rail
C Rail
Operating cost = \$474,347,246(2022) ~\$493,794,348.7(2023)
PMT = 307,334,036
Impact/mile = $\frac{Operating\ cost}{PMT} = \frac{\$493{,}794{,}348.7}{307{,}334{,}036}$ = \$1.61
Cost/trip = cost/mile × trip distance
= \$ 1.61× 30.7 miles

- Agency cost/trip = \$49.43

H Rail
Operating cost = ~\$347,439,650.6 (2023)
PMT = 266,053,405
Impact/mile = $\frac{Operating\ cost}{PMT} = \frac{\$347{,}439{,}650.6}{266{,}054{,}405}$ = \$1.31
Cost/trip = cost/mile × trip distance
= \$ 1.31× 1.39 miles

- Agency cost/trip = \$1.82

Total Agency cost/trip = \$51.25

Environmental Dimension - Impact to Environment
GHG Emissions
Mode 1: Auto (Drive)
Using the CO_2 emission factor for a medium sedan
CO_2 emissions per mile= $\frac{Carbon\ intensity(CO_2)}{Fuel\ economy\ (MPG)} = \frac{8{,}887}{22}$ = 0.404kg/passenger mile

- CO_2 /trip = $\frac{emissions}{mile} \times$ *trip distance(miles)*
=*\$*0.404kgCO_2/mile× 38.9 miles = 15.72kgCO_2

$IM_i = W_i \times I_i \times C_i$ = 1 ×15.72kgCO2 × \$0.22 = \$3.51

Mode 2 : C Rail + H Rail
C Rail
CO_2 emissions per mile= 0.150kg
CO_2 /trip = $\frac{emissions}{mile} \times$ trip distance(miles)= \$ 0.150kg× 30.70miles = 4.61kgCO_2
$IM_i = W_i \times I_i \times C_i$ = 1 ×4.61kgCO_2 × \$0.22 = \$1.01

H Rail
CO_2 emissions per mile= 0.099kg
CO_2 /trip = $\frac{emissions}{mile} \times$ trip distance(miles)= \$ 0.099kg× 1.39miles = 0.14kgCO_2
$IM_i = W_i \times I_i \times C_i$ = 1 ×0.14kgCO_2 × \$0.22 = \$0.03

Social Dimension- Impact to traveler/trip taker
Travel Cost
Mode 1: Auto (Drive)

Medium sedan, average vehicle cost/mile = ¢72/mile
Vehicle cost: fuel, maintenance, depreciation, insurance.
Parking @ Quincy = \$300/20 work trips = \$15/day (value changes due to parking lot location)

- Cost/trip = ¢0.72 *38.9 +\$15
  = \$43.01

Mode 2: C Rail + H Rail
Base Fare Estimate - Monthly Pass
Commuter Rail Zone 7: \$360
Assumptions: cost/day = $\frac{360}{40} = \$9$/trip

- cost/trip = \$9

Health - Active travel
Mode 1: Auto
Active travel = 0
No active travel benefit

Mode 2: C Rail + H Rail
C Rail
Walk from Point a to stop = 0.5miles
Walk from Point b to stop = 0.02miles
Walk score of a = 0.86
Walk score of b = 0.99

- Active travel/trip = walk distance × *walk score*
  (0.5× 0.86) + (0.02× 0.99) = 0.45miles

$IM_i = W_i \times I_i \times C_i = 1 \times 0.45 \times \$0.71 = -\ \$0.32$
H Rail
Walk from stop to destination = 0.2miles
Walk score from stop = 0.99

- Active travel/trip = walk distance × walk score
  0.20× 0.99 = 0.20miles

$IM_i = W_i \times I_i \times C_i = 1 \times 0.20 \times \$0.71 = -\ \$0.14$

Reliability- Delay time (min)
Mode 1: Auto

- Delay time = *Best guess− Optimistic*
  = *55 – 45* = 10 mins ~ 0.1667hr

IM= $W_i \times I_i \times C_i = 1 \times 0.1667 \times \$30.26 = \$5.04$

Mode 2: C Rail + H Rail
Data not available ~ no delay
H Rail

- Delay time = RT50- *RT10*
  = *43.907 – 40.402* = 3.5mins ~0.058hr

IM= $W_i \times I_i \times C_i = 1 \times 0.058 \times \$30.26 = \$1.76$

Reliability- Variation in delay time (min)

Mode 1: Auto

- VAR time = Pessimistic time − *Optimistic time*

  = *70 – 45* = 25 mins~0.42hr

IM= $W_i \times I_i \times C_i$ = 1 × 0.417 × \$30.26 = \$12.62

Mode 2: C Rail + H Rail

Data not available ~ no delay

H Rail

- Delay time = RT90 - *RT10*

  = *48.77 – 40.40* = 8.37 mins ~0.14hr

IM= $W_i \times I_i \times C_i$ = 1 × *0.14*× \$30.26 = \$4.24

Safety (physical harm)- Injuries(#/mile)

Mode 1: Auto

Injuries in 2022 = *133,158 but we consider only total physical which = 30,384*

VMT= 56,949,000,000

- Injury/mile = $\frac{Injury}{VMT} = \frac{30,384}{56,949,000,000}$ = 5.33E-07
- Injury/trip = Injury/mile × trip distance = 5.33E-07 × 38.9 miles = 2.07337E-05
- $IM_i = W_i \times I_i \times C_i$ = 1 × 2.07E-05× \$96,630.40 = \$2.00

Mode 2 : C Rail + H Rail

C Rail

Data not available ~ no injuries

H Rail

Injuries in 2022 = 202/year

PMT= 266,053,405

- Injury/mile = $\frac{Injury}{VMT} = \frac{202}{266,053,405}$ =7.5925E−07
- Injury/trip = *Injury/mile × trip distance =7.5925E−07× 1.39miles* = 1.06E−06
- $IM_i = W_i \times I_i \times C_i$ = 1 × 1.06E−06 ×\$96,630.40 = \$0.102

Safety - loss of life (LOL) per distance

Mode 1: Auto

Fatalities in 2022 = 409/year

VMT= 56,949,000,000

- Loss of life/mile = $\frac{Fatalities}{VMT} = \frac{409}{56,949,000,000}$ =7.18E−09
- Loss of life/trip = *LOL/mile × trip distance = 7.18E−09 × 38.9 miles* = 2.7937E−07
- $IM_i = W_i \times I_i \times C_i$ = 1 × 2.79E−07 × \$19,373,295.50 = \$5.41

Mode 2 : C Rail + H Rail

C Rail

Fatalities in 2022 = 5/year

25% of 5 = 1.25 fatalities

- Loss of life/mile = $\frac{Fatalities}{VMT} = \frac{1.25}{307,334,036}$ =4.07E−09

- Loss of life/trip = *LOL/mile × trip distance = 4.07E−09 × 30.70 miles* = 1.25E−07
- $IM_i = W_i \times I_i \times C_i$ = 1 × *1.25E−07* × \$19,373,295.50 = \$2.42

H Rail
No fatalities/trip

Public Health- PM2.5 eq/mile
Mode 1: Auto
Gasoline Light duty
PM2.5 exposure = 5.18E-08 tons/ mile

- PM2.5/trip = PM2.5 exposure × trip distance
  = 5.18E-08 tons/ mile × 38.9mi = 2.02E-06 tons/trip
- $IM_i = W_i \times I_i \times C_i$ = 1 × 2.02E-06 × \$516,914.26 = \$1.04

Mode 4 : C Rail + H Rail
C Rail
Energy Intensity for Rail: 1589BTU per passenger mile (US,2019)
1 gallon of diesel fuel = 138,700 BTUs
Mean Fuel consumption(rail) = 0.0115 gallons/passenger-mile
MBTA weighted PM2.5 emission factor = 3.385 grams/gallon

- PM2.5 Emissions per Mile = Fuel Consumption Rate × PM2.5 Emission Factor
  = 0.0115× 3.385 grams/gallon = 0.039grams/mile

Total PM2.5 = 0.039gram/mile × 30.7mile
= 1.20 grams ~ 1.32E-06

- $IM_i = W_i \times I_i \times C_i$ = 1 × 1.32E-06 × \$516,914.26 = 0.68

H Rail
Energy Intensity for Rail: 779BTU per passenger mile (US,2019)
1 gallon of diesel fuel = 138,700 BTUs
Mean Fuel consumption(rail) = 0.0056 gallons/passenger-mile
MBTA weighted PM2.5 emission factor = 3.385 grams/gallon

- PM2.5 Emissions per Mile = Fuel Consumption Rate × PM2.5 Emission Factor
  = 0.0056× 3.385 grams/gallon = 0.019grams/mile

Total PM2.5 = 0.019gram/mile × 1.39mile
= 0.03 grams ~ 3E-08

- $IM_i = W_i \times I_i \times C_i$ = 1 × 3E-08 × \$516,914.26 = 0.01

By applying the quantification methodology to Trip 1, we can comprehensively evaluate the economic, environmental, and social impacts. The results highlight the importance of considering multiple dimensions in transportation planning to enhance sustainability and efficiency.

Local Trip 1

Trip Details:

- Route: Quincy Market, 206 S Market St to Metropolitan Waterworks Museum
- Time: Peak AM
- Distance: 6.3 miles by car and bike, 5.91 for rail

- Mode: driving, biking and public transit

Economic Dimension

Direct Agency Cost

Mode 1: Auto (Drive Alone)

Operating cost = \$3,654,925,000(2021) ~\$4,109,794,802(2023)

VMT = 56,949,000,000

Impact/mile = $\frac{\text{Operating cost}}{\text{VMT}} = \frac{\$4{,}109{,}794{,}802}{56{,}949{,}000{,}000}$ = \$0.072

Impact/trip = cost/mile × trip distance

= \$0.072 × 6.3 miles

- Agency cost/trip = \$0.45

Mode 2: Light Rail

Operating cost = \$199,157,007 (2022) ~\$207,321,968(2023)

PMT = 76,107,994

Impact/mile = $\frac{\text{Operating cost}}{\text{PMT}} = \frac{\text{"207,321,968"}}{76{,}107{,}994}$ = \$2.72

Cost/trip = cost/mile × trip distance

= \$ 2.72× 5.91 miles

- Agency cost/trip = \$16.07

Mode 3: Biking

H Rail

Operating cost = \$14,324,681.64(2023)

BMT = 1,748,250,000

Impact/mile = $\frac{\text{Operating cost}}{\text{PMT}} = \frac{14{,}324{,}681.64}{1{,}748{,}250{,}000}$ = \$0.0082

Cost/trip = cost/mile × trip distance

= \$ 1.31× 6.3 miles

- Agency cost/trip = \$0.05

Environmental Dimension - Impact to Environment

GHG Emissions

Mode 1: Auto (Drive)

Using the CO_2 emission factor for a medium sedan

CO_2 emissions per mile= $\frac{\text{Carbon intensity}(CO_{2})}{\text{Fuel economy (MPG)}} = \frac{8{,}887}{22}$ = 0.404kg/passenger mile

- CO_2 /trip = $\frac{\text{emissions}}{\text{mile}}$× trip distance(miles)=

=\$0.404kgCO_2/mile× 6.3 miles = 2.54kgCO_2

$IM_i = W_i \times I_i \times C_i$ = 1 ×2.54kgCO2 × \$0.22 = \$0.57

Mode 2: L Rail

CO_2 emissions per mile= 0.163kg

CO_2 /trip = $\frac{\text{emissions}}{\text{mile}}$× trip distance(miles)= \$ 0.163kg× 5.91miles = 0.96kgCO_2

$IM_i = W_i \times I_i \times C_i$ = 1 ×0.96kgCO_2 × \$0.22 = \$0.22

Mode 3: Biking
No CO_2 emissions per mile

Social Dimension- Impact to traveler/trip taker
Travel Cost
Mode 1: Auto (Drive)
Medium sedan, average vehicle cost/mile = ¢72/mile
Vehicle cost: fuel, maintenance, depreciation, insurance.
Parking = $20/day (value changes due to parking lot location)

- Cost/trip = ¢0.72 *6.3 +$20
  = $24.71

Mode 2: L Rail
Base Fare Estimate – one-way fare

- cost/trip = $2.40

Mode 3: Biking
No travel cost

Health - Active travel
Mode 1: Auto
Active travel = 0
No active travel benefit

Mode 2: L Rail
Walk from Point a to stop = 0.3miles
Walk from Point b to stop = 0.5miles
Active travel = 0.513miles
$IM_i = W_i \times I_i \times C_i$ = 1 × 0.513 × \$0.71 = - \$0.36

Mode 3: Biking

- Active travel/trip = 4.5 miles

$IM_i = W_i \times I_i \times C_i$ = 1 × 4.5 × \$0.71 = - \$3.17

Reliability- Delay time (min)
Mode 1: Auto

- Delay time = Best guess− Optimistic
  = ~ 0.1hr

$IM = W_i \times I_i \times C_i$ = 1 × 0.1× \$30.26 = \$3.03

Mode 2: L Rail
Data not available ~ no delay
H Rail

- Delay time = RT50- RT10
  = ~0.079hr

$IM = W_i \times I_i \times C_i$ = 1 × 0.079× \$30.26 = \$2.39

Mode 3: Biking
No delay

Reliability- Variation in delay time (min)
Mode 1: Auto

- VAR time = Pessimistic time − Optimistic time
  = 0.25hr

$IM= W_i \times I_i \times C_i$ = 1 × 0.25× \$30.26 = \$7.57

Mode 2: L Rail

- Delay time = RT90 - RT10
  = ~0.17hr

$IM= W_i \times I_i \times C_i$ = 1 × 0.17× \$30.26 = \$5.14

Mode 3: Biking
No variation in delay time

Safety (physical harm)- Injuries(#/mile)
Mode 1: Auto
Injuries in 2022 = 133,158 but we consider only total physical which = 30,384
VMT=56,949,000,000

- Injury/mile = $\frac{\text{Injury}}{\text{VMT}} = \frac{30{,}384}{56{,}949{,}000{,}000}$ = 5.33E-07
- Injury/trip = Injury/mile × trip distance = 5.33E-07 × 6.3 miles =3.3579E-06
- $IM_i= W_i \times I_i \times C_i$ = 1 ×3.3579E-06 × \$96,630.40 = \$0.32

Mode 2 : L Rail
Injuries in 2022 = 104/year
PMT= 266,053,405

- Injury/mile = $\frac{Injury}{VMT} = \frac{104}{76{,}107{,}994}$ =1.3667E−06
- Injury/trip = Injury/mile × trip distance =1.3667E−06× 5.91miles = 8.08E-06
- $IM_i= W_i \times I_i \times C_i$ = 1 ×8.08E-06 ×\$96,630.40 = \$0.81

Mode 3: Biking
No injuries

Safety - LOL per distance
Mode 1: Auto
Fatalities in 2022 = 409/year
VMT= 56,949,000,000

- Loss of life/mile = $\frac{Fatalities}{VMT} = \frac{409}{56{,}949{,}000{,}000}$ =7.18E−09
- Loss of life/trip = LOL/mile × trip distance = 7.18E−09 × 6.3miles = 4.5E−08
- $IM_i= W_i \times I_i \times C_i$ = 1 ×4.5E−08 × \$19,373,295.50 = \$0.87

Mode 2 : L Rail
No fatalities/trip

Mode 3: Biking
No fatalities

Public Health- $PM_{2.5}$ eq/mile
Mode 1: Auto
Gasoline Light duty
PM2.5 exposure = 5.18E-08 tons/ mile

- PM2.5/trip = PM2.5 exposure × trip distance
  = 5.18E-08 tons/ mile × 6.3mi = 3.26E-07tons/trip
- $IM_i = W_i \times I_i \times C_i$ = 1 × 3.26E-07 × \$516,914.26 = \$0.17

Mode 2: L Rail
Energy Intensity for Rail: 1307BTU per passenger mile (US,2019)
1 gallon of diesel fuel = 138,700 BTUs
Mean Fuel consumption(rail) = 0.0094 gallons/passenger-mile
MBTA weighted PM2.5 emission factor = 3.385 grams/gallon

- PM2.5 Emissions per Mile = Fuel Consumption Rate × PM2.5 Emission Factor
  = 0.0094× 3.385 grams/gallon = 0.032grams/mile

Total PM2.5 = 0.019gram/mile × 5.91mile
= 0.112 grams ~ 1.23E-07

- $IM_i = W_i \times I_i \times C_i$ = 1 × 1.23E-07 × \$516,914.26 = \$0.11

Mode 3: Biking
No PM 2.5 exposure to others

Local Trip 2

Trip Details:

- Route: Fenway Park to Boston South Station
- Time: Peak AM
- Distance: 3.3 miles by car, 2.5 by bike, 1.65 by light rail and 2.56 by commuter rail and bike, 5.91 for rail: Driving, Biking, C Rail & L Rail

Economic Dimension
Direct Agency Cost
Mode 1: Auto (Drive Alone)
Operating cost = \$3,654,925,000(2021) ~\$4,109,794,802(2023)
VMT = 56,949,000,000

Impact/mile = $\frac{Operating\ cost}{VMT} = \frac{\$4,109,794,802}{56,949,000,000}$ = \$0.072

Impact/trip = cost/mile × trip distance
= \$0.072 × 3.3 miles

- Agency cost/trip = \$0.24

Mode 2: C Rail
Operating cost = \$474,347,246(2022) ~\$493,794,348.7(2023)
PMT = 307,334,036
Impact/mile = $\frac{Operating\ cost}{PMT} = \frac{\$493{,}794{,}348.7}{307{,}334{,}036}$ = \$1.61
Cost/trip = cost/mile × trip distance
= \$ 1.61× 2.56 miles

- Agency cost/trip = \$4.10

Mode 3: Biking
H Rail
Operating cost = \$14,324,681.64 (2023)
BMT = 1,748,250,000
Impact/mile = $\frac{Operating\ cost}{PMT} = \frac{\$14{,}324{,}681.64}{1{,}748{,}250{,}000}$ = \$0.0082
Cost/trip = cost/mile × trip distance
= \$ 0.0082× 2.3 miles

- Agency cost/trip = \$0.02

Mode 4: Light Rail
Operating cost = \$199,157,007 (2022) ~\$207,321,968(2023)
PMT = 76,107,994
Impact/mile = $\frac{Operating\ cost}{PMT} = \frac{"207{,}321{,}968"}{76{,}107{,}994}$ = \$2.72
Cost/trip = cost/mile × trip distance
= \$ 2.72× 1.65 miles

- Agency cost/trip = \$4.49

Environmental Dimension - Impact to Environment

GHG Emissions

Mode 1: Auto (Drive)
Using the CO_2 emission factor for a medium sedan
CO_2 emissions per mile= $\frac{Carbon\ intensity(CO_2)}{Fuel\ economy\ (MPG)} = \frac{8{,}887}{22}$ = 0.404kg/passenger mile

- CO_2 /trip = $\frac{emissions}{mile}$ × trip distance(miles)=
=\$0.404kgCO_2/mile× 3.3 miles = 1.33kgCO_2

$IM_i = W_i \times I_i \times C_i$ = 1 ×1.33kgCO_2 × \$0.22 = \$0.30

Mode 2: C Rail
CO_2 emissions per mile= 0.150kg
CO_2 /trip = $\frac{emissions}{mile}$× *trip distance(miles)= \$ 0.150kg× 2.56miles* = 0.38kgCO_2
$IM_i = W_i \times I_i \times C_i$ = 1 ×0.38kgCO_2 × \$0.22 = \$0.09

Mode 3: Biking

No CO_2 emissions per mile

Mode 4: L Rail

CO_2 emissions per mile= 0.163kg

CO_2 /trip = $\frac{emissions}{mile}$× trip distance(miles)= \$ 0.163kg× 1.65miles = 0.27kgCO_2

$IM_i = W_i \times I_i \times C_i$ = 1 ×0.27kgCO_2 × \$0.22 = \$0.06

<u>Social Dimension- Impact to traveler/trip taker</u>

Travel Cost

Mode 1: Auto (Drive)

Medium sedan, average vehicle cost/mile = ¢72/mile

Vehicle cost: fuel, maintenance, depreciation, insurance.

Parking = \$20/day (value changes due to parking lot location)

- Cost/trip = ¢0.72 *3.3 +\$20
  = \$43.01

Mode 2: C Rail

Base Fare Estimate – one-way fare

- cost/trip = \$2.40

Mode 3: Biking

No travel costs

Mode 4: L Rail

Base Fare Estimate – one-way fare

- cost/trip = \$2.40

Health - Active travel

Mode 1: Auto

Active travel = 0

No active travel benefit

Mode 2: C Rail

- Active travel/trip = 0.19miles

$IM_i = W_i \times I_i \times C_i$ = 1 × 0.19 × \$0.71 = - \$0.13

Mode 3: Biking

- Active travel/trip = 2.15miles

$IM_i = W_i \times I_i \times C_i$ = 1 × 2.15 × \$0.71 = - \$1.51

Mode 4: L Rail

- Active travel/trip = 0.8miles

$IM_i = W_i \times I_i \times C_i$ = 1 × 0.8 × \$0.71 = - \$0.56

Reliability- Delay time (min)

Mode 1: Auto

- Delay time = Best guess− Optimistic

= ~ 0.1hr

IM= $W_i \times I_i \times C_i$ = 1 × 0.1× \$30.26 = \$3.03

Mode 2: L Rail
Data not available ~ no delay

Mode 3: Biking
No delay

Mode 4: L Rail

- Delay time = RT50- RT10
  ~0.065hr

IM= $W_i \times I_i \times C_i$ = 1 × 0.065× \$30.26 = \$1.97

Reliability- Variation in delay time (min)
Mode 1: Auto

- VAR time = Pessimistic time − Optimistic time
  = ~0.27hr

IM= $W_i \times I_i \times C_i$ = 1 × 0.27× \$30.26 = \$8.17

Mode 2: C Rail
Data not available

Mode 3: Biking
No variation in delay time

Mode 4: L Rail

- Delay time = RT90 - RT10
  = 0.14hr

IM= $W_i \times I_i \times C_i$ = 1 × 0.14× \$30.26 = \$4.24

Safety (physical harm)- Injuries(#/mile)
Mode 1: Auto
Injuries in 2022 = 133,158 but we consider only total physical which = 30,384
VMT=56,949,000,000

- Injury/mile = $\frac{Injury}{VMT} = \frac{30{,}384}{56{,}949{,}000{,}000}$ = 5.33E-07
- Injury/trip = Injury/mile × trip distance = 5.33E-07 × 3.3miles = 1.76E-06
- IM_i= $W_i \times I_i \times C_i$ = 1 ×1.76E-06 × \$96,630.40 = \$0.17

Mode 2 : C Rail
Data Not available

Mode 3: Biking
No injuries

Mode 4 : L Rail

Injuries in 2022 = 104/year
PMT= 266,053,405

- Injury/mile = $\frac{Injury}{VMT} = \frac{104}{76,107,994}$ =1.3667E−06
- Injury/trip = Injury/mile × trip distance =1.3667E−06× 1.65miles = 2.26E-06
- $IM_i = W_i \times I_i \times C_i$ = 1 ×2.26E-06 ×$96,630.40 = $0.23

Safety - LOL per distance
Mode 1: Auto
Fatalities in 2022 = 409/year
VMT=56,949,000,000

- Loss of life/mile = $\frac{Fatalities}{VMT} = \frac{409}{56,949,000,000}$ =7.18E−09
- Loss of life/trip = LOL/mile × trip distance = 7.18E−09 × 3.3 miles = 2.37E−08
- $IM_i = W_i \times I_i \times C_i$ = 1 × 2.379E−08 × $19,373,295.50 = $0.46

Mode 2 : C Rail
Data not available

Mode 3: Biking
No fatalities

Mode 4 : L Rail
No fatalities/trip

Public Health- $PM_{2.5}$ eq/mile
Mode 1: Auto
Gasoline Light duty
PM2.5 exposure = 5.18E-08 tons/ mile

- PM2.5/trip = PM2.5 exposure × trip distance
  = 5.18E-08 tons/ mile × 38.9mi = 2.02E-06 tons/trip
- $IM_i = W_i \times I_i \times C_i$ = 1 × 2.02E-06 × $516,914.26 = $1.04

Mode 2: L Rail
Energy Intensity for Rail: 779BTU per passenger mile (US,2019)
1 gallon of diesel fuel = 138,700 BTUs
Mean Fuel consumption(rail) = 0.0056 gallons/passenger-mile
MBTA weighted PM2.5 emission factor = 3.385 grams/gallon

- PM2.5 Emissions per Mile = Fuel Consumption Rate × PM2.5 Emission Factor
  = 0.0056× 3.385 grams/gallon = 0.019grams/mile

Total PM2.5 = 0.019gram/mile × 1.39mile
= 0.03 grams ~ 3E-08

Mode 3: Biking
No PM 2.5 exposure to others

Neighborhood Trip

Trip Details:

- Route: (Franklin Park Zoo to The Museum of Bad Art)
- Time: Peak AM
- Distance: 2.3 miles all modes
- Mode: driving, bus, biking

Economic Dimension

Direct Agency Cost

Mode 1: Auto (Drive Alone)

Operating cost = \$3,654,925,000(2021) ~\$4,109,794,802(2023)

VMT = 56,949,000,000

Impact/mile = $\frac{\text{Operating cost}}{\text{VMT}} = \frac{\$4{,}109{,}794{,}802}{56{,}949{,}000{,}000}$ = \$0.072

Impact/trip = cost/mile × trip distance

= \$0.072 × 2.3 miles

- Agency cost/trip = \$0.17

Mode 2: Bus

Operating cost = \$554,824,649(2022) ~\$577,571,132.7(2023)

PMT = 185,268,319

Impact/mile = $\frac{\text{Operating cost}}{\text{PMT}} = \frac{\$577{,}571{,}132.7}{185{,}268{,}319}$ = \$3.17

Cost/trip = cost/mile × trip distance

= \$ 3.17× 2.3 miles

- Agency cost/trip = \$7.16

Mode 3: Biking

H Rail

Operating cost = \$14,324,681.64 (2023)

BMT = 1,748,250,000

Impact/mile = $\frac{Operating\ cost}{PMT} = \frac{\$14{,}324{,}681.64}{1{,}748{,}250{,}000}$ = \$0.0082

Cost/trip = cost/mile × trip distance

= \$ 0.0082× 2.3 miles

- Agency cost/trip = \$0.02

Environmental Dimension - Impact to Environment

GHG Emissions

Mode 1: Auto (Drive)

Using the CO_2 emission factor for a medium sedan

CO_2 emissions per mile= $\frac{Carbon\ intensity(CO_2)}{Fuel\ economy\ (MPG)} = \frac{8{,}887}{22}$ = 0.404kg/passenger mile

- CO_2 /trip = $\frac{emissions}{mile}$ × trip distance(miles)=

=\$0.404kgCO_2/mile× 2.3 miles = 0.93kgCO_2

$IM_i = W_i \times I_i \times C_i$ = 1 ×0.93kgCO_2 × \$0.22 = \$0.21

Mode 2: Bus

CO_2 emissions per mile= 0.29kg
CO_2 /trip = $\frac{emissions}{mile}$ × trip distance(miles)= \$ 0.29kg× 2.3 miles = 0.67kgCO_2
$IM_i = W_i \times I_i \times C_i$ = 1 ×0.67kgCO_2 × \$0.22 = \$0.15

Mode 3: Biking
No CO_2 emissions per mile

<u>Social Dimension- Impact to traveler/trip taker</u>
Travel Cost
Mode 1: Auto (Drive)
Medium sedan, average vehicle cost/mile = ¢72/mile
Vehicle cost: fuel, maintenance, depreciation, insurance.
Parking @ Franklin Zoo = \$25 (trip dependent)

- Cost/trip = ¢0.72 * 2.3 + \$25
  = \$26.72

Mode 2: Bus
Base Fare Estimate – one-way fare
cost/trip = \$1.70

Mode 3: Biking

Health - Active travel
Mode 1: Auto
Active travel = 0
No active travel benefit

Mode 2: Bus

- Active travel/trip = walk distance × walk score
  = 0.41miles

$IM_i = W_i \times I_i \times C_i$ = 1 × 0.41 × \$0.71 = - \$0.29

Mode 3: Biking

- Active travel/trip = walk distance × walk score
  = 1.5 miles

$IM_i = W_i \times I_i \times C_i$ = 1 × 1.5 × \$0.71 = - \$1.06
Reliability- Delay time (min)
Mode 1: Auto

- Delay time = Best guess− Optimistic
  = ~ 0.12hr

$IM = W_i \times I_i \times C_i$ = 1 × 0.12× \$30.26 = \$3.63

Mode 2: Bus
Data not available ~ no delay
H Rail

- Delay time = RT50- RT10
  = ~0.071hr

$IM = W_i \times I_i \times C_i$ = 1 × 0.071× \$30.26 = \$2.15

Mode 3: Biking
No delay

Reliability- Variation in delay time (min)
Mode 1: Auto

- VAR time = Pessimistic time − Optimistic time
  = ~0.22hr

$IM = W_i \times I_i \times C_i$ = 1 × 0.22× \$30.26 = \$6.66

Mode 2: L Rail

- Delay time = RT90 - RT10
  = ~0.478hr

$IM = W_i \times I_i \times C_i$ = 1 × 0.478× \$30.26 = \$14.47

Mode 3: Biking
No variation in delay time

Safety (physical harm)- Injuries(#/mile)
Mode 1: Auto
Injuries in 2022 = 133,158 but we consider only total physical which = 30,384
VMT=56,949,000,000

- Injury/mile = $\frac{Injury}{VMT} = \frac{30{,}384}{56{,}949{,}000{,}000}$ = 5.33E-07
- Injury/trip = Injury/mile × trip distance = 5.33E-07 × 2.3 miles = 1.23E-06
- $IM_i = W_i \times I_i \times C_i$ = 1 × 1.23E-06 × \$96,630.40 = \$0.12

Mode 2 : Bus
Injuries in 2022 = 277/year
PMT= 185,268,319

- Injury/mile = $\frac{Injury}{VMT} = \frac{277}{185{,}268{,}319}$ =1.50E-06
- Injury/trip = Injury/mile × trip distance =1.50E-06× 2.3 miles = 3.45E−06
- $IM_i = W_i \times I_i \times C_i$ = 1 × 3.45E−06 ×\$96,630.40 = \$0.33

Mode 3: Biking
No injuries

Safety - LOL per distance
Mode 1: Auto
Fatalities in 2022 = 409/year
VMT= 56,949,000,000

- Loss of life/mile = $\frac{Fatalities}{VMT} = \frac{409}{56{,}949{,}000{,}000}$ =7.18E−09
- Loss of life/trip = LOL/mile × trip distance = 7.18E−09 × 2.3 miles = 1.65E−08

- $IM_i = W_i \times I_i \times C_i$ = 1 × 1.65E−08 × \$19,373,295.50 = \$0.32

Mode 2 : Bus
No fatalities/trip

Mode 3: Biking
No fatalities

Public Health- $PM_{2.5}$ eq/mile
Mode 1: Auto
Gasoline Light duty
PM2.5 exposure = 5.18E-08 tons/ mile

- PM2.5/trip = PM2.5 exposure × trip distance
  = 5.18E-08 tons/ mile × 2.3 mi = 1.19E-07 tons/trip
- $IM_i = W_i \times I_i \times C_i$ = 1 × 1.19E-07 × \$516,914.26 = \$0.09

Mode 2: Bus
Diesel Bus
PM2.5 exposure = 8.155-08 tons/ mile
Max Average Bus Load : 56
PM2.5/ person = $\frac{8.155\text{−}08\ tons}{56}$ = 1.456E-09tons/passenger mile

- PM2.5/trip = PM2.5 exposure × trip distance
  = 1.456E-09 tons/p-mile × 2.3 mi = 3.35E-09tons/trip
- $IM_i = W_i \times I_i \times C_i$ = 1 × 3.35E-09tons × \$516,914.26 = \$0.00173

Mode 3: Biking
No PM 2.5 exposure to others

Implementation and Technology Transfer

This section discusses the practical application of the methodologies developed in this study through the use of an automated Excel workbook. This tool is designed to streamline the calculations and processes described in previous sections, making it easier for practitioners to implement the study's findings in real-world scenarios.

Excel Workbook for Automated Calculations
The Excel workbook serves as a practical implementation tool that automates the calculations required for the HIM. It includes predefined formulas and an intuitive interface that allows users to input relevant data and obtain results without extensive manual computation.

Functionality

- Automated Calculations: The workbook automates complex calculations for economic, environmental, and social impacts based on user inputs.
- User-Friendly Interface: The workbook is designed with a simple interface to ensure accessibility for users with varying levels of technical expertise.

- Comprehensive Analysis: The workbook facilitates the holistic analysis of transportation impacts by integrating all relevant metrics and providing a consolidated cost output.

User Manual

A comprehensive user manual is provided with the workbook, detailing step-by-step instructions on how to use the tool. The manual includes:

- Installation Instructions: Guidelines on how to download and set up the workbook.
- Input Guidelines: Descriptions of the data required and how to enter it correctly.
- Calculation Processes: Explanations of how the workbook processes the data and computes the results.
- Output Interpretation: Guidance on how to interpret the results generated by the workbook.

The Excel workbook offers several significant benefits, making it a valuable tool for implementing the study's methodologies. First, it simplifies the application of the methodologies, making them accessible to a wider audience, including those who may not have advanced technical skills. This ease of use ensures that a broader range of practitioners can effectively utilize the tool. Second, by providing a standardized format for calculations, the workbook ensures consistent application of methodologies across different projects and users, promoting uniformity and reliability in the results. Lastly, the workbook is designed to be scalable, allowing it to be used in various contexts and by different stakeholders, including policymakers, planners, and engineers. This scalability ensures that the tool can be adapted to different needs and scenarios, enhancing its overall utility.

Technology Transfer

The Excel workbook and manual have been handed over to MassDOT ensuring easy access for all stakeholders. To facilitate the effective use of the workbook, training sessions and support materials will be provided. These will include instructional videos and Q&A sessions to address any user queries. One of these sessions has already been conducted.