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Sustainability and Public Transportation Theory and Analysis

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Theory and Analysis

by

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Abstract

In the 21st century there is a need to provide sustainable transportation systems in cities to ensure that they remain centres of innovation, quality of life, and economic development. Public transit is often framed as a high potential mode of sustainable urban travel and while much research has been done on other modes of travel, comprehensive research into its sustainability benefits of public transit has been limited. This thesis first reviews the literature on sustainability and sustainable transport to develop a framework to analyze public transit and then applies the framework to 33 mass transit systems from the USA using the National Transit Database. The Public Transit Sustainable Mobility Analysis Project (PTSMAP) framework developed in this thesis utilizes environmental, economic, social and system effectiveness factors to compare the relative performance of Heavy Rail and Light rail systems while demonstrating how composite sustainability index techniques can be applied to public transit analysis. An application of this framework to a real world transit planning scenario is also presented using data from the TransLink UBC Line Phase 2 study report. Both demonstrations of the PTSMAP framework demonstrate a new way to analyze transit based on sustainability and aid in future research and decision making scenarios.

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For everyone working to make our cities more sustainable, vibrant, and liveable.

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Equations

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Acronyms

Acronym	Definition in Thesis
ADA	Americans with Disabilities Act
AHP	Analytic hierarchical process
BRT	Bus Rapid Transit
APTA	American Public Transit Association
CNG	Compressed natural gas
CSI	Composite Sustainability Index
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GWP	Global Warming Potential
HRT / HR	Heavy Rail Transit / Heavy Rail
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ITDP	Institute for Transport and Development Policy
ITS	Intelligent Transportation Systems
LRT / LR	Light Rail Transit /Light Rail
MADM	Multiple Attribute Decision Making Process
MAUT	Multi Attribute Utility Theory
MAVT	Multi Attribute Value Theory
MCDM	Multi Criteria Decision Making
MOP	Multi Objective Programming
MSA	Metropolitan Statistical Area
NTD	National Transit Database
PKM	Passenger kilometers travelled
PTSMAP	Public Transit Sustainable Mobility Analysis Project
OECD	Organization for Economic Cooperation and Development
ROW	Right of way
RRT	Rail Rapid Transit
SIBRT	Integrated Transport Systems and BRT Systems Alliance
TRB	Transportation Research Board
UZA	Urbanized Area

Table of Symbols

Symbol	Definition in Thesis
w	Weighting for various factors
f	Represents factors used in the thesis
E_i	represents environmental factors i-j used in this study
S_i	represents social factors i-j used in this study
N_i	represents economic factors i-j used in this study
Y_i	represents economic factors i-j used in this study
A_s	Service Area
P_s	Service Area Population
L_r	Route Length
L_d	Directional Route km
n_{op}	Vehicles Operated Max Service
n_{max}	Vehicles Available Max Service
pkm	Passenger KM Travelled
τ	Unlinked Passenger Trips
Vkm	Vehicle or Train Rev km
Vh	Vehicle Or Train Rev Hours
E	Energy for propulsion
L	Fuel for propulsion
λ	Operating Cost
r	Revenue
c	Vehicle capacity
ρ	Vehicle annual revenue km travelled
$E_{E\,j}$	Energy consumed by system j per passenger km travelled
$E_{g\,j}$	Energy consumed by system j per passenger km travelled
$E_{SO2\,j}$ $E_{NOX\,j}$ $E_{HG\,j}$	Energy consumed by system j per passenger km travelled
$N_{o,j}$	Operating costs per passenger km travelled on system j
$N_{f,j}$	Average fare per trip on system j
$N_{t,j}$	Average travel time cost per trip on system j
$N_{z,j}$	Cost recovery on system j
$N_{g,j}$	Transit use per economic activity on system j
$S_{a,j}$	Accessibility factor for system j
$S_{f,j}$	Average fare / income per capita for system j
$S_{l,j}$	Average travel length per trip for system j
$S_{u,j}$	% of stations that are ADA compliant on system j
$Y_{c,j}$	Capacity utilization factor for system j
$Y_{t,j}$	Trips per service population capita for system j

"We can't solve problems by using the same kind of thinking we used when we created them."

~Albert Einstein

Chapter 1: Introduction

1.1 Background and Motivation

Cities rely on effective and efficient transportation systems to drive social and economic development. Transportation has been called the “lifeblood” of cities in recognition of the role it plays shaping communities and enabling opportunities for their inhabitants (Vuchic V. R., 1999). In the Twentieth Century, along with an increase in standard of living and rapid economic development, much of the western world experienced rapid growth and progress in the development of urban and intercity transportation systems. New technologies allowed higher degrees of personal mobility, while new policies and infrastructure investment led to the development of vast urban and regional transportation networks that enabled a speed and magnitude of travel that had never before existed. However, these increases in mobility have been accompanied by challenges, problems, and issues that have impacted the social, environmental and economic wellbeing of individuals and communities.

In the latter half of the 20th century, many of these transportation challenges became very apparent. Advances in economics, environmental sciences, engineering, social sciences and planning have brought increased awareness and nuance to many of the impacts of transportation, ranging from global climate change to local economic inefficiency. Of particular note is the challenge associated with automobile centric development. Cities around the world suffer from heavily congested roads as urban centers are becoming more reliant on the automobile as a primary mode of transportation (Moavenzadeh, Hanaki, & Baccini, 2002). Communities have been segregated by large automobile oriented freeways contributing to a variety of social issues, while the pollution from cars that use freeways contribute to local and global environmental issues (Banister, 2005). In Canada, for example, 28% of all greenhouse gas emissions originate from transportation – the second largest source of emissions after stationary power generation (Environment Canada, 2012). On an urban level, similar emissions are observed with 36% of all emissions in the City of Toronto originating from trucks and cars (ICF International, 2007).

These impacts are a by-product of the rapid development of transportation in the 20th century, where urban form was designed and engineered to accommodate the automobile as the principle and, in some cases, sole transportation mode (Newman & Kenworthy, 1999). With congestion and automobile dependence come increased emissions and pollution, impacts on human health, and economic hindrance, all of which are symptoms of one overarching problem: unsustainable transportation systems (Banister, 2005).

In the developed world one needs not look further than the daily occurrence of congested roadways carrying commuters to see a clear example of this problem. Many cities have grown to accommodate high levels of automobile use in such a way that the sustainability of transportation of entire cities and regions has been negatively impacted (Newman & Kenworthy, 1999). This pattern of automobile focussed transportation development observed in North American cities has led to deeply rooted problems that detrimentally affect the livability of cities (Vuchic V. R., 1999).

In the developing world, mobility issues and transportation related problems affect the quality of life, economic processes and opportunities available to citizens (Robinson & Thagesen, 2004). Poor access to adequate transportation infrastructure and services limits the mobility of citizens and the accessibility of essential needs and basic public services (e.g. health, education). Poorly planned and maintained transportation systems also stifle economic growth (World Bank, 2002). It has been argued that the creation of strong transportation infrastructure is an essential aspect of a community's development, both in terms of economic activity and the opportunities available to community members (Simon, 1996).

In the early 21st century more than half of humanity lived in cities. It is expected that in the 21st century the vast majority of humans will continue to live in urban, instead of rural, areas (Moavenzadeh & Markow, 2007). As a shift from rural living to urban centres already occurred in the developed world during the 20th century, the majority of this shift will occur in developing countries. As populations in urban centres in Asia, Africa, and Latin America continue to increase into the 21st century the need for well-planned and engineered transportation solutions is apparent if cities will avoid the same unsustainable pattern of auto-oriented transport development.

Transportation systems found in cities in many developed countries are plagued with sustainability challenges covering a wide spectrum of issues – social, economic, and environmental (Banister, 2005). Research has shown that, in North American cities, transit and not the automobile contribute to more sustainable transportation across economic, social, and environmental dimensions, however there are always trade-offs between modes. For example, a study of the City of Toronto demonstrated that public transit outperformed private transport on environmental and economic scales. However, under social criteria neither mode was clearly superior (Kennedy C. A., 2002).

These challenges are an important reminder that the development of sustainable transportation systems should be better understood in order to minimize the negative impacts of transport. The development of new sustainability oriented systems and the retrofitting of old systems to be more sustainable is emerging as a trend in developed nations. For example, the use of ITS to manage demand and new investments in larger and more efficient public transport systems points towards a strong interest in more sustainable travel.

Not all nations are resigned to unsustainable transport; many governments, agencies, and institutions are taking a proactive stance on facilitating the development of sustainable transportation systems. The TransMilenio BRT System in Colombia, and the many new BRT systems being developed in Africa and Latin America, are all examples of a shift towards public transport as a mechanism for sustainable development. BRT development has also expanded to North America with different BRT variants being constructed in many cities. However, there are many instances of rapid growth in auto use that have brought forward sustainability challenges. For example, in some Indian cities private auto vehicle use is on the rise, and with this increase in use has come severe congestion and air pollution (Agarwal & Zimmerman, 2008). Further, there is currently little knowledge on the relative sustainability benefits of different types of mass transit systems found within the literature and field of practice.

1.2 Problem Statement

With the trends of rapid urbanization in developing countries and automobile dominance in many developed nations there is a need to explore policies and plans that will allow transportation to enable quality of life for urban citizens in a sustainable manner. Mass public transportation systems, such as Heavy Rail, LRT and BRT systems, are often cited in research and planning documents as true alternatives to auto dependence for both urbanizing and developed cities. Despite awareness of the value of sustainable transportation and the technical operation of transit systems, few studies exist that compare and contrast the sustainable transportation contributions of major mass transit systems. Typical studies focus on one or two indicators, such as energy consumed or capacity, but do not look at the sustainability of a system in a holistic manner. An assessment of literature on the topic of sustainable transportation shows several robust theoretical frameworks for the analysis of transportation which are applicable for comparing different modes, but few implementations of these frameworks. This thesis synthesizes these frameworks in order to create a methodology that is useful for both planning transit systems to maximize sustainability while also investigating the performance of three major mass transit modes (BRT, LRT, HR) under a variety of sustainability parameters.

1.3 Objectives and Contributions

This research seeks to apply an understanding of sustainability to public transportation planning in order to provide deeper understanding to the issues presented in section 1.2. The two guiding questions of this research are:

1. How are the contributions of public transit to sustainable mobility measured?
2. How do different rapid transit modes and systems compare in the delivery of sustainable mobility?

Specifically, the objectives of this thesis are:

1) To utilize existing sustainability knowledge along with analysis methodologies and studies focused on sustainable transportation to develop and test a framework that can assess the contributions to sustainable transportation of rapid transit systems. This framework utilizes performance criteria that relate to the major dimensions of sustainable transportation in order to develop composite sustainability indices.
2) To use the framework from goal 1 to analyze a set of public transit systems from various contexts in order to develop an understanding of how these systems contribute to sustainable transportation. The results of this analysis can be used in transport systems planning in a range of contexts, including rapidly urbanizing cities, new rapid transit projects, systems expansion, as well as in further sustainable transportation research.
3) To apply the outputs of goal 1 and 2 on specific case studies and decision making problems to demonstrate the variety of applications for sustainable transportation assessment in research and planning. This included demonstrating the framework as decision support tool.

These objectives are structured around three contributions to the transportation planning profession and transportation field of research:

1) A new framework for sustainability assessment that synthesizes past studies and methodologies is presented and critiqued. The framework is shared for use with both historical and model data, as well as using analytical equations. This framework may be used in future research endeavours or planning.
2) A sample use of the tool for the comparison of a set of 33 public transportation systems using publically available data.
3) A case study applying sustainability assessment and sustainable transportation concepts to real world transport system planning.

The following additional goals have been developed for this thesis project:

- To develop familiarity with a variety of mass transit system concepts in a global context.
- To develop an understanding of the sustainability performance of mass transit systems in a global context.

- To complement course based learning and transportation planning experience with an in-depth study into sustainability and sustainable transportation.

1.4 **Scope and Methods Overview**

Sustainability is a vast interdisciplinary area of study that combines concepts from many disciplines including biology, chemistry, engineering, development studies, and planning. As a result, any inquiry into a sustainability topic has a large boundary of investigation. For the purposes of this thesis project, a clear scope has been developed in order to frame and guide research endeavors.

The scope of this thesis is broken up into three components. First, a survey of literature in three areas is included: sustainability and sustainable development, sustainable transportation and mobility concepts, and transportation decision technique within the field of sustainable transportation research. The scope of these sections is to probe existing literature and represent contemporary understanding, research, and methodologies within each area. As all three areas are quite broad, the study is not exhaustive and has been limited to areas that are directly relevant to the problem this research is exploring. These sections are included to provide a logical argument and progression of thoughts for the type of sustainability analysis included in this study. As the majority of past research in this area has focussed on defining, contextualizing, and framing sustainable transportation as part of sustainable development, as well as the methods to measure it, there is a body of information to draw upon.

The second component is an outline of a composite sustainability index analysis tool for mass transit system analysis. This tool is designed to utilize model and historical data, such as ridership counts or energy consumption, along with technical details, such as route length and design, to calculate a numerical representation of sustainability. This tool also can utilize planning data to provide commentary on the overall sustainability of plan alternatives when compared to existing systems or amongst plan alternatives. As indicators and metrics are the common form of sustainability assessment methodologies, this tool takes a similar approach. This research sorts sustainability impacts, positive and negative, into four overall categories (environment, economy, social, and system effectiveness) in order to streamline analysis. Analytical equations that are based on past transport research are also included in the scope when necessary to expand data analysis. These equations provide a method to conceptually understand and estimate sustainability performance based on a set of input values. Modelling techniques and software are not the focus of this thesis so their use is only commented on and not explored rigorously. Three normalizing techniques were used in the calculation of composite sustainability indicators during the assessment process - z-score, linear utility, and re-scaling. This approach allows inputs and negative and positive impacts of public transit to be combined into a single index and is an effective tool for exploring both research questions.

Lifecycle costs of the physical infrastructure itself are not included in this study as the focus of this study is on the sustainability performance of the system itself, as opposed to the infrastructure. Therefore embedded impact, such as CO_2 production or water consumption, within guide ways, station areas, or other pieces of infrastructure are not included in this analysis. The conclusion of the research comments on how they may be integrated into future research.

While this tool could be applied to any number of transport systems worldwide, data is difficult to access and often costly to collect. Therefore the tool is demonstrated using readily available public data – using 33 systems from NTD dataset from the United States of America. This set includes 13 Heavy Rail and 20 Light Rail Transit systems, which were analyzed across 14 indicators from 4 categories of sustainability - environmental, economic, social, and system effectiveness. Sensitivity testing on composite equation weighting is included to demonstrate how different weights can impact the development of the index. The comparison of factor performance to urban factors, such as accessibility to density, are also in scope. This part of the research is intended to provide further discussion on how mass transit is enabled by urban environment, while also commenting on the influence of factors on overall representation of sustainability but is not the overall focus of this research.

The final component is a set of case studies that demonstrate how the tools and theory contained in this thesis can be applied. The scope of this component includes a case study on urban environment and transit use and public transport's role in creating sustainable communities.

1.5 **Overview of Thesis**

This thesis is composed of 9 chapters, including this introductory chapter. Chapter 2 of the thesis contains the literature review for sustainability and sustainable development. This chapter is intended to frame the discussion on sustainability and provide the common theories, frameworks, and methodologies common to sustainability research. This chapter is included as background material in the form of a critical literature review.

Chapter 3 of the thesis is a literature review on the definitions of sustainable transportation and transportation planning topics. This chapter is intended to outline the key theories that shape the analysis of sustainable transportation in the composite sustainability analysis tool. Like chapter 2, this chapter is a literature review intended to establish background information that informs the methods used to analyze the research problem.

Chapter 4 contains a literature review of decision making and analysis tools used in sustainable transportation research and planning. Various frameworks, as well as the theories behind the use of indicators and indices are explored in this chapter.

Chapter 5 synthesizes the findings of the literature review in order to create a methodology that is useful for tackling the research questions of this thesis project. This methodology contains indicators utilized for transit analysis in this study, along with an outline of how to use the tool. This tool is applied in chapter 6 to the National

Public Transit Database from the USA in order to explore the relative strengths of LRT and Heavy Rail networks in a variety of cities.

Chapter 6 outlines how the database was used and shares findings including composite sustainability indices from two methodologies and relation of sustainability parameters to urban factors such as density.

Chapter 7 applies the analysis methodology to data from the Metro Vancouver region in British Columbia, Canada in order to demonstrate how this tool can be utilized in decision making. This chapter complements the research demonstration in chapter 6.

Chapter 8 is a case study of sustainability concepts in the city of Calgary. Concepts from the literature review are articulated using commentary on the sustainability of the City of Calgary. This exercise is included to highlight sustainability analysis techniques.

Chapter 9 provides concluding thoughts on this research. The contributions of this research are reframed along with limitations, potential applications, and future follow up research.

Chapter 2: Sustainability and Sustainable Development

2.1 Chapter Overview

The concept of sustainable development is at the heart of this research. In order to assess the contributions to sustainable transportation of various public transport systems, a clear understanding of sustainability and sustainable development must first be researched and articulated. The goal of this research is not to challenge the discussion on key sustainability concepts, such as climate change, but rather to apply them into an analysis framework. Therefore, this literature review seeks to gather current thinking and ideas on key sustainability concepts in order to inform the development of a transportation analysis tool.

This chapter presents a literature review on the common concepts of sustainable development based on text books, research articles, and reports from academia as well as the field of practice consisting of civil society organizations, governments, and consultants.

The goal of this chapter is to provide an overview of the key concepts to sustainability which will serve as background for chapter 3's discussion of sustainable transportation. As the field of sustainability intersects with many disciplines and areas of research activities, this chapter's scope is limited to the broader ideas of sustainability. Chapters 3 and 4 dive deep into the specifics of sustainability as it pertains to transportation engineering and planning research.

First, this chapter will share the most common and accepted definitions of sustainable development and sustainability in section 2.2. Section 2.3 then outlines a variety of frameworks and key concepts such as footprint analysis, which are useful for understanding and applying sustainability concepts. The final section presents how these ideas are applied within this research and concludes the chapter.

2.2 Sustainability and Sustainable Development Definitions

2.2.1 Defining Sustainability and Sustainable Development

Sustainability is a complex field of research, with many contributing theories, that explores how human society is able to thrive while not compromising the systems that are essential to maintain quality of life. This exploration of sustainability attempts to draw upon the diversity of theories and definitions of sustainability in order to present a balanced perspective on the many definitions of sustainability found in the literature.

Given the interdisciplinary nature of the field, there are many nuanced definitions of sustainability. Many of the foundational concepts embedded into the present notion of sustainability have roots prior to the emergence of the term. The concept of sustainability can be traced back into the mid twentieth century where awareness of human industry's impacts on the environment became more apparent due to breakthroughs in a number of fields (The World Conservation Union, 2006).

Sustainability is commonly explored in terms of the theories of sustainable development. A commonly used definition of sustainability comes from the Brundtland Commission's report "Our Common Future - "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). While this definition was not the first use of the idea of sustainable development, it is seen as the first widely utilized definition and the report is commonly referred to as the first credible study on this subject (Theis, 2012).

While there is common acknowledgement of the Brundtland definition of sustainability as both a foundational definition for work in the sustainability field, in both practice and research, essential literature in the sustainable transportation field also use this definition as a starting point. This literature, which is cited throughout this review, includes Newman and Kenworthy (1999), Black (2010), Banister (2005), and Jeon (2007), as well as others.

Newman and Kenworthy 1999 both paraphrases and expands upon the definition by providing a history of sustainability as well as a summary of the report itself and key literature in the field. Sustainable development or sustainability is paraphrased as social and economic development in the global context should improve and not harm the environment (Newman & Kenworthy, 1999). Newman and Kenworthy suggest sustainability has its routes at the 1972 UN Conference on the Human Environment where 113 nations pledged to contribute to cleaning up the environment and contributing to environmental issues on a global scale. Issues of pollution and resource depletion caused by human activity were of concern; however these challenges were also contrasted with human development challenges or goals whose solutions may come at odds with environmental goals (Newman & Kenworthy, 1999). This dichotomy of human activity being held at odds with the environment led to the development of the World Commission on Environment and Development, which eventually published the Brundtland report in 1987 (Newman & Kenworthy, 1999).

As mentioned previously, many authors suggest this report as the key launching point for sustainability in academia, policy, and practice. Newman and Kenworthy suggest this report gave form to a set of language and ideas, which would later be explored at the 1992 Earth Summit, for balancing the tension between environment, social, and economic development, in effect creating a platform for exploring how nations and communities can meet their development goals without repeating the same resource consumption and pollution patterns of the past. The authors suggest that global sustainability is oriented around 4 principles:

1. “The Elimination of poverty, especially in the Third World, is necessary not just on human grounds but as an environmental issue”
2. “The First World must reduce its consumption of resources and production of wastes.”
3. “Global Cooperation on environmental issues is no longer a soft option.”

4. “Change towards sustainability can occur only with community based approaches that take local cultures seriously.”

(Newman & Kenworthy, 1999)

These principles can be used as guiding points to understand the complex interactions imbedded within sustainable development – namely the need to simultaneously advance environmental and human development outcomes at global and local community levels.

Theis (2012), Black (2010), Jeon (2007), Kennedy (2005), Newman & Kenworthy (1999), Banister (2005), the 1987 Brundtland report, and others consider sustainable development issues fitting under the same three overarching boxes or categories – economy, environment, and society. These categories are seen as a useful way to further subdivide the definition and increase its applicability. Sustainable development is able to balance the competing issues from within each category and ensure the goals of sustainability are met (Banister, 2005) (Newman & Kenworthy, 1999). This is referred to commonly as a triple bottom line approach and is further described throughout the thesis.

Theis (2012) suggests that the Brundtland Report emphasizes that sustainability is a normative concept or social construct targeted at ensuring human development. Technological and economic progress can enable sustainability, however the social element (access to education, justice, healthcare) and ecological access (equitable distribution of ecological goods and services) are all essential for sustainable development and safe guarding generational interests (Theis, 2012).

While other definitions of sustainability do exist (see p 16-17 of (Moavenzadeh & Markow, 2007) for a summary of many definitions particularly those that pertain to urban and transport issues) most are oriented around the Brundtland definition or have expanded upon it. Although, there are some departures in the literature which Markow and Moavenzadeh summarize:

- Some authors suggest that sustainability is often anthropocentric and that all nature or life should be considered under quality of life
- Other authors push for a temporal element and that the intergenerational equity element of the Brundtland definition must be heavily considered, especially with respect to how future generations should be compensated for changes to the environment.

(Moavenzadeh & Markow, 2007, p. 20)

The authors suggest that the second point on intergenerational equity is a point of debate in the literature with two dominant schools representing the poles of the discussion. One school is the neoclassicists who argue that future generations should have at least as much capital wealth as present generations, which would imply that human assets can substitute natural assets. The second school is an ecological school that argues future generations should have access to the same level of human and natural wealth as the present generation.

In practice most discussions of sustainability are oriented around balancing human development issues (social and economic) with ecological concerns.

2.2.2 Applying the Definition

While the commonly applied ideas of sustainability resonate with a key definition, the application of the concept can often be muddled and is indeed at the heart of this thesis project. This sub chapter introduces key concepts on the application of the concept of sustainability and draws links to key concepts and frameworks that can elucidate its application throughout this thesis.

Banister (2005) comments on the definition of sustainability – " it has been used by most researchers and decision-makers interested in the environment and like many of the terms that are used and supported, it is difficult to define precisely" (Banister, Unsustainable Transport: City transport in the new century, 2005, p. 2). Transferring the definition of sustainability into a useful tool for evaluating projects or in this thesis' case, transit, is a challenge given the scope of the definitions commonly used, as well as the number of definitions. Moavenzadeh and Markow in 2007 suggested that while there are many definitions of sustainability based on their review of definitions found throughout the literature, most definitions have similar key ideas represented within them. Their definition is as follows:

"*Sustainable development seeks to preserve environmental quality- whether for less advantaged populations, future generations, or the sake of environmental diversity itself – while pursuing opportunities for economic advancement, all leading to improved quality of life*" (Moavenzadeh & Markow, 2007, p. 15).

Within this definition is a key link to the triple bottom line framework of sustainability that explicitly looks at sustainability as a balancing act between social (quality of life), economic (Economic advancement), and environmental concerns (environmental quality).

The authors argue that sustainability policies must be "holistic" in their ability to consider local and regional impacts across environmental, social, and economic categories (Moavenzadeh & Markow, 2007). The crux of their suggestion is that for sustainability to be applied to decision making, the techniques used must employ criteria and methodologies that distil a holistic understanding of the issues at hand, rather than focussing on a specific aspect of the challenge, issue, or project being considered, such as an economic consideration (Moavenzadeh & Markow, 2007). The authors further argue that in applying sustainability and sustainable development to decision making that there needs to be greater recognition for the value of the environment, concepts of equity applied to different segments of society as well as to future generations, a greater understanding of sustainability by decision makers, and a stronger set of project evaluation methods for the sustainability context.

Kenworthy and Newman (1997) have outlined the application of sustainability principles in a variety of settings, including in cities, which is an important element of sustainability at the heart of this research.

2.3 Select Sustainability Frameworks

The ideas and tools used to understand sustainability come from a variety of disciplines, including ecology, environmental sciences, economics, development studies, and engineering. Inasmuch, there are many different tools used to explore sustainability both qualitatively and quantitatively. Three ideas used to understand sustainability are presented briefly – the triple bottom line, which is adapted for this thesis, footprint analysis, which is used to understand sustainability using ecological concepts, and the strong and weak sustainability framework. Within sustainability, there are tensions and differing perspectives on the nature of sustainability as a field of theory. The discussion on weak vs. strong sustainability in this sub chapter is one such discussion within the field. This thesis aims to present prominent theories and provide commentary on their relevance and contribution to sustainable transportation.

2.3.1 Triple Bottom Line

The triple bottom line framework deconstructs sustainability into three spheres- ecological/environmental, economic, and social (Pei, Amekudzi, Meyer, Barella, & Ross, 2010). Pei, Amekudzi, Meyer, Barella, and Ross (2010) suggest the advantages of this framework are that its approach to categorizing and developing indicators for sustainability are easily applied to it and it can be applied in a multi criteria decision making (MCDM) approach. MCDM is discussed in chapter 4.

The triple bottom line framework is a natural extension of the previous definitions of sustainability that were outlined with three bottom lines (environmental/ecological), social, economic that are commonly used as bins or boxes to collect issues or sustainability ideas. The key issues contained within each “box” have been approached differently by a number of authors dependent on their overarching philosophy, discipline, and perspective on sustainability among other influences. Theis (2012) provides a summary of the key ideas contained within each element drawing on a number of sources, including the Brundtland report. These ideas are summarized in Table 2-1.

Table 2-1 Summary of Key Category Considerations

Economic	Environmental	Social (Socio-political)
- Decision-making frameworks - Flows of financial capital - Facilitation of Commerce	- Diversity and interdependence of living systems - Goods and services produced by ecosystems - Impacts of human wastes	- Interactions between institutions and firms - Functions expressive of human values - Aspirations and well-being - Ethical issues - Decision-making dependent on collective action

(Text adapted from Theis, 2012)

The environmental or ecological dimension considers the impacts of human activities and developments on changing local and global environments (Low, 2003). Low argues that human society and its growth is limited by environmental constraints on a local and global level and as a result the environmental dimension of sustainability must be approached from both local and global perspectives. Common environmental issues include consumption of resources, anthropogenic climate change and the degradation of local environments due to pollution.

When discussing sustainability, a key issue that accompanies these discussions is climate change. The world's leading climate scientists have reached consensus that human activity in the form of greenhouse gas (GHg) emissions is warming the planet in ways that will have profound and unsettling impacts on natural resources, energy use, ecosystems, economic activity, and potentially quality of life (Transportation Research Board, 2008)

Climate is defined as the average weather over long time scales and changes in climate are driven by a variety of complex processes which involve insolation, albedo, and the composition of the Earth's atmosphere (Snodgrass, 2012). The climate system is a set of complex interactions involving landmasses, snow and ice, bodies of water, and living beings on the planet (IPCC, 2007). According to the Intergovernmental Panel on Climate Change (IPCC) the climate is always evolving over time based on its own internal dynamics and changes in external factors which are called forcings. An example of an external forcing would be a natural phenomenon such as a volcanic eruption that displaces ash into the atmosphere (IPCC, 2007). Solar radiation drives the Earth's climate and changes to the way solar energy interacts with the Earth's climate system are what causes climate change (Snodgrass, 2012) (Thompkins, 2012) (IPCC, 2007). Climate change can manifest in a number of ways – changes in precipitation, a reduction in snow cover, or an increase in overall global surface temperature – are a few examples (Lenzen, Dey, & Hamilton, 2003).

While discussing climate change and the composition of the Earth's atmosphere, it is important to consider the greenhouse effect. The greenhouse effect is a natural phenomenon where the Earth's atmosphere responds to different wavelengths of electromagnetic radiation and retains energy, essentially warming the Earth (Lenzen, Dey, & Hamilton, 2003). Since 1750, due to industrialization, there has been a marked atmospheric increase of greenhouse gases including CO_2 and methane (IPCC, 2007) (Lenzen, Dey, & Hamilton, 2003). According to Lensen, Dey, & Hamilton (2003), since human activity began to utilize wide scale combustion of fossil fuels in the eighteenth century, the concentration of CO_2 in the atmosphere has increased from approximately 280 ppm to approximately 365 ppm in 1998. This increase in CO_2 has also led to an increase in radiative forcing due to concentrations of greenhouse gases, which has an impact on global climate (IPCC, 2007).

Economic development is the process of a community's growth or progress towards economic goals, such as increased wealth, employment, productivity or ultimately welfare (Litman, 2013). Under a triple bottom line framework, the primary economic considerations are ensuring development occurs that advance economic activity in coherence with the two other sustainability categories over time (Banister, 2005). Within the literature, there are varying definitions on what sustainable economic development entails. Some perspectives outline that growth can come with established intentional trade-offs in other sustainability sectors (see previous discussions and the discussion on strong vs. weak) while others suggest that economic development towards goals such as employment cannot come at the cost of the environment as human capital cannot replace environmental capital (Low, 2003).

The social dimension of sustainability often is described as dealing with issues of equity and inclusion. Equity can be considered, as previously discussed, among current populations on a global scale, a local scale, but also an intergenerational scale (Moavenzadeh & Markow, 2007) (Low, 2003). Moavenzadeh and Markow suggest a direct linkage between sustainability and the welfare of future generations, through an intergenerational lens, as the concept of sustainability is defined around the status of future generations not being worsened by present actions. On a global scale, the discussion of equality and sustainable development often focuses on the status of nations and large regions, and the historic conditions that have impacted the wellbeing of their inhabitants.

Low (2003) presents a discussion on social sustainability through a lens of ensuring that society is not only served by economic progress (as opposed to society serving economic progress) but that elements of local and global society are integrated in a just and equitable manner. Rather than focussing on sustaining a set social system, social sustainability is focussed on 'sustaining progress towards the kind of fair society in which the good of each (individually) coincides with the good of all (collectively).' (Low, 2003).

In the literature these three dimensions have been displayed in different ways including pillars, concentric circles, and overlapping circles (The World Conservation Union, 2006). One approach, dating back to the 1970s, put forward by Passet as summarized by Joumard and Nicolas, represents the three ideas as three concentric circles inside one another, with environment being the largest, the social, and finally economy (Joumard & Nicolas, Transport project assessment methodology within the framework of sustainable development, 2010). This approach indicates a hierarchy, whereas the pillars represent the contribution of each element to sustainable development . Finally, the interlocking circles approach recognizes the need to balance all three elements, as well as the often interlinked natures of issues within each aspect of sustainability (The World Conservation Union, 2006). As with all frameworks, these differing views express alternative ways to view sustainability and imbed the concept within research and policy.

On top of these three categories, many frameworks reviewed for this thesis also include elements of decision making and policy formulation as well as systemic issues as essential for sustainability. These tools are used in conjunction with the triple bottom line framework, or are used in alternative frameworks. Banister (2005) describes these two areas of consideration as participatory involvement of all actors (diverse stakeholder groups) as well as good governance mechanisms. These two areas occur under different forms throughout other frameworks including work by Litman (2013) and Kennedy et al. (2005). While not integrated into the 'triple bottom line' framework, they are seen as expansions to it and part of achieving sustainable development processes and are included in this discussion. Other studies, such as those by Jeon (2007) and Jeon et al (2009) expand the triple bottom line to include system factors. Such approaches are becoming more common in analysis and are worth noting.

2.3.2 Footprint Analysis

Footprint analysis is a concept used in discussing sustainability that reflects the amount of land required to provide a unit of populations (person, household, community, etc.) consumption (Rees, 1992). Since its original publication, the tool has seen use in a number of contexts and has been expanded, refined, and challenged in policy and research,

Rees' work was the definitive introduction to this topic that framed the issue of humanity's urban existence through the lens of urban ecology – a system of flows of energy and material in the process of resource allocation. Rees argues that economics, in theory, as a field of study plays a similar role for the study of society's allocation of resources however it has become reductionist in nature and does not take into consideration many of the principles that ecology might take into account – such as the inseparable link between human activity and the environment it takes place in.

From this framing, Rees suggested that traditional environmental economics may view environmental issues in urban development as an issue of 'deteriorating amenities' – such as a loss of open space or air pollution. – with a common solution being cost internalization or other economic incentives. The ecologic point of view espoused in Rees' work puts forth an exploration of the connection between sustainability and human activity through an analysis of material/energy flows, rather than just considering deterioration. Under this analysis the concept of carrying capacity, the population that can be sustained on a given amount of land, is used to suggest that if all human society lived within a regional carrying capacity that society would in effect be sustainable (Rees, 1992). Rees uses a concept of human carrying capacity as follows:

> *"maximum rate of resource consumption and waste discharge that can be sustained indefinitely in a region without progressively impairing the functional integrity and productivity of the relevant ecosystem"* (Rees, 1992, p. 125)

From this definition, the land required for continual production of materials like food and energy, as well as the land required to absorb pollution, like greenhouse gases, are often considered in footprint analysis and the output is measured in units of area – typically hectares – required to produce these inputs. Rees outlines how this framework shows how the footprint of a city is usually larger than the city's contained area.

The ecological footprint concept essentially measures the amount of capacity required for all the material and energy flows, as well as impacts, which a given population of humans needs to maintain their life style. For example, Rees cites calculations for the Fraser Valley Region to illustrate the concept – 'if the entire world population of 5.2 billion consumed productive land at the rate of our Fraser

Valley Example, the total requirement would be 25.5 billion hectares' (Rees, 1992, p. 129). Rees is quick to mention the Earth's finite capacity of 13 billion hectares. With a finite amount of carrying capacity on the planet, this tool challenges policy makers, researchers, and decision makers to reconsider urban development.

However, in practice, the framework has been criticized – Fiala (2008) developed a critique of the methodology and reviewed previous critical studies of the framework. The overall critique of the framework included a number of relevant points that could be used to refine the framework in practice, or could be used as rationale for selecting another framework for understanding sustainability. First, Fiala identifies an inability to address the overall sustainability of consumption and issues that arise with consumption. Second, a lack of attention to land degradation due to production for human consumption is noted – if land is degraded in producing for human consumption, it is possible using more land can have an efficiency gain than using less land, in effect damaging less land in the long run. According to Fiala, this would indicate a larger foot print could be more sustainable depending on the usage and the types of land involved. Another point raised is that a common focus on sequestration of greenhouse gas emissions or land required for greenhouse gases may limit the scope of analysis. Fiala's ultimate conclusion is that for research, it may be more useful to use sustainability measures rather than footprint due to its limitations.

Despite these critiques, the footprint analysis still sees wide use as a means of communicating impacts of human activity as well as disparity between carrying capacity of a population and the overall carrying capacity of the planet. The simple output, expressing sustainability as a comparison of two land areas, is clearly communicated which is where the true value of this framework lies.

2.3.3 *Weak* vs. *Strong- two characterizations of sustainability*

In the literature, a framework for characterizing sustainability that emerges is strong and weak sustainability. The Sustainable Transportation Indicators Subcommittee of the Transportation Research Board (TRB) in 2009 described the weak vs. strong dichotomy in terms of substitutions being allowed or disallowed. The following definitions and examples were employed:

- **Weak** –natural capital (natural resources, ecological systems) can be replaced by human capital (i.e. industrial productive capacity). In a transport example, a system improvement is allowed if it enables economic development or if negative impacts can be offset by other sectors. A second example provided was on fish stocks –wild fish can be replaced if equal or greater fish populations are provided in the aquaculture.
- **Strong** – natural capital cannot be substituted with human capital. In a transport context, this would mean that reductions of impacts from transport would be the focus of transport projects. The fish example used states that the intrinsic value of wild fish should be maintained.

(Sustainable Transportation Indicators Subcommittee , 2009)

Both concepts are useful for exploring sustainability evaluation and can be built into frameworks for evaluation and researching sustainable transportation benefits of mass transit systems. These two descriptions of sustainability can also be compared to the neoclassical and ecological schools of sustainability previously discussed, with weak sustainability presenting a strong alignment with the neoclassical outlook and strong sustainability aligning with the ecological outlook.

2.4 **Conclusion**

Sustainability is a complex field spanning many academic fields including environmental science, biology, chemistry, physics, sociology, economics, and branches of engineering. Inasmuch, a complete treatment of sustainability is not possible in this thesis, rather the intention is to present key and commonly recurrent concepts in a clear manner that have informed the development of ideas presented in subsequent chapters.

The concepts of sustainability that have been developed over the past 40 years provide a powerful tool set to better understand human society's internal impacts, intergenerational impacts, and impact on the planet caused by the pursuit of development. By combining a variety of fields in interdisciplinary study and policy formulation sustainability allows researchers, consultants, and decision makers to better understand complex problems and make more informed decisions in conjunction with diverse stakeholders in order to improve the outlook for humanity and the planet.

Chapter 3: **Overview of Sustainable transportation Concepts**

3.1 Chapter Overview

Chapter three outlines the basic concepts of mass transit which are essential for further discussions on sustainability assessment of mass transit systems. These foundational concepts are derived from a literature review that spanned a variety of sources including textbooks, journal articles, and guidelines/reports from public and private sectors. This section covers the different types of mass transit along with traditional public transit analytical tools that are relevant to sustainability analysis.

3.2 Sustainable Transportation: mobility, systems, and definitions

3.2.1 What is a Sustainable Transportation System?

Transportation systems enable cities to flourish and grow – enabling day to day activities, economic interactions, and quality of life. Vibrant and liveable cities are supported by effective transportation systems (Vuchic V. R., 1999). This is recognized in academic research, the field of practice, and in public discourse. It is common for transportation issues to be top of mind during election cycles and in livability and ranking scales, such as the Mercer quality of living survey and the Economist Intelligence Unit's global livability report, include a variety of transportation issues when ranking cities or livability. Transportation is a common element of day to day life and is recognized as essential for liveability and progress. However, defining and applying definitions of sustainable transport can create a degree of confusion due to the inherit complexity of both topics.

The analysis of transportation systems is an in depth topic with many elements including human behaviour, network configuration, geography of the system, prevailing influences on the system (politics and economics, for example), and the types of mode of travel that are available (Manheim, 1979). Transportation systems can be considered as consisting of:

- Physical elements
    - Infrastructure (roads, runways, rail roads)

        - Vehicles
- Individual Choices
    - When to travel
    - Where to travel
    - How to travel
- Institutions that enable travel through the provision of information, goods, and services that influence choices
    - Markets
    - Companies
    - Governments
    - Other actors and institutions that influence choice

      (Manheim, 1979) (Cidell, 2012)

With the interaction of all these elements, transportation system analysis and planning is a complex process.

As previously explored, sustainability is also a very complex topic that explores all elements of human welfare (the social aspects of sustainability), human economic expansion, and the impacts of human growth and development on the environment. Given the degree of complexity in both topics, combining the two into a common field creates a challenging topic to address (Cidell, 2012). The question of sustainable transport can be traced back to the question of how transportation is viewed. Hensher (2005) provides two view points on transport – one is the Napoleonic view that transport drives the broader social, political, and economic framework. Under this view transport is a means to achieve policy and should be regulated and controlled. The second view Hensher puts forward is the Anglo Saxon view that transport is 'just another market sector' and it should be provided as effectively as possible with little interference. Recalling the discussion on sustainable development, the former view of transport is adopted for the discussion of sustainable transportation.

However, even before sustainability became a topic of common discourse in the late 1980s, the need to address a variety of impacts of transportation systems was suggested and even enforced or strongly encouraged by eminent authors or researchers in the field. For example, Manheim (1979) wrote in his influential text "Fundamentals of Transportation Systems Analysis - Volume 1: Basic Concepts" on setting up boundaries for transport system analysis and a variety of the impacts transport system changes may have that should be considered by the analyst or researcher. Manheim's approach encouraged viewing transportation systems as holistic entities, with a focus on multimodal solutions that take into account social, economic, political, environmental, and other considerations. This approach was written before the age of sustainability language, but is in line with the principles of sustainability and the goals set out in the Brundtland report, and other authors who have since studied and expanded upon the sustainability concept.

While issues of environmental, social, and economic impacts have been present in transportation discourse prior to the emergence of sustainability as a major area of study, since the late 80s there has been great interest in the growing field of sustainable transportation.

Schiller, Bruun, and Kenworthy (2010) explore the emergence of sustainable transportation in terms of three main concepts:

1. Concerns on transport's impacts and the counter productivity of conventional highway-oriented planning that emerged from the 1970s onward
2. Recognition that reducing traffic in cities (either through calming, or pedestrianization) achieved health and environmental benefits
3. Increased sustainability awareness of sustainability concepts after the Brundtland report was published
   (Schiller, Bruun, & Kenworthy, 2010)

With these three factors, as well as the state of practice and study in transportation leaning towards holistic analysis, the field of sustainable transport was able to emerge. Since then several studies that have set out to establish indicators, definitions, and analyses of theoretical and existing systems based on sustainability terms have been undertaken.

Black suggests that a sustainable transport system is one that applies the Brundtland definition or simply said “transport that satisfies the current transport and mobility needs without compromising the ability of future generations to meet those needs” (Black W. , 2010). As transport has a variety of negative impacts, specific focus on economic, social, and environmental issues should be included in a definition of sustainable transport and its application to decision making (Bongardt, Schmid, Cornie, & Litman, 2011).

According to Schiller, Bruun, and Kenworthy (2010), a sustainable transportation system contributes to community needs and aspirations, while limiting its negative impacts on the environment and society as well as its financial costs. This outline of sustainable transportation fits into the triple-bottom line conception of sustainability. Shiller, Bruun, and Kenworthy also suggest that technical factors (i.e. fuel efficiency, or improved traffic systems) can play a major role, but that it is important to consider multiple dimensions such as land use planning and broader public visioning in order to create truly sustainable transportation systems and communities.

Within the literature there is no accepted single definition of sustainable transport or how to measure it (Bongardt, Schmid, Cornie, & Litman, 2011). However, one definition commonly referred to in the literature is that of the Centre for Sustainable Transportation, which outlines three key elements of sustainable transport:

- Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Limits emissions and waste within the planet’s ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of

> renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.
>
> (The Centre for Sustainable Transportation, 2005)

In essence, there is more to sustainability than limiting emissions through technical progress – instead the whole system must be improved and integrated into the broader community. To create sustainable transportation involves society at large – including aspects of planning, policy, economics, and citizen involvement, not just technical progress (Schiller, Bruun, & Kenworthy, 2010).

Transferring this definition into use can involve the general sustainability frameworks outlined earlier in chapter 2, such as the triple bottom line framework. Previous sustainable transportation studies have utilized such frameworks to effectively develop useful analytical tools from definitions. One of the major studies on sustainable transportation in the Civil Engineering field was conducted by Jeon in 2007. This dissertation suggests that all frameworks should in the bare minimum consider:

- How effective the transportation system is
- Impacts of the system on economic development
- Impacts of the system on social quality of life
- Impacts of the system on environmental integrity

(Jeon, 2007)

The 2007 Jeon framework is comprehensive, recognizable, and useable in that it utilizes the three common terms from the triple bottom line framework, but it also explicitly treats transport effectiveness as a key element of sustainability.

Banister outlines a sustainable transportation paradigm composed of four aspects:

- Actions to reduce the need to travel
- Encouragement of modal shift

- Short trip lengths
- Increased efficiency

(Banister, Cities, Mobility, and Climate Change, 2008)

Another thorough attempt to outline a definition of sustainable transportation comes from Kennedy et al. (2005). Sustainable transport is framed as a critical urban issue intersecting with complex global issues, such as climate change, as well as local issues like human health. Similar to other frameworks, the authors frame sustainable urban transport as a balance between economy, environment and society, however the difference is in how this balance is developed. Four pillars are suggested:

- **Governance**: "the establishment of effective bodies for integrated land-use transportation planning"
- **Funding**: "the creation of fair, efficient, and stable funding mechanisms"
- **Infrastructure:** "strategic investment in major infrastructure"
- **Neighborhoods**: "the support of investments through local design"

(Kennedy, Miller, Shalaby, Maclean, & Coleman, 2005)

Finally, Banister (2005) provides 7 key principles for establishing sustainable transport policy:

1. Reduce the need to travel
2. Reduce the absolute levels of car use and road freight in urban areas
3. Promote more energy efficient modes of travel for both passenger and freight
4. Reduce noise and vehicle emissions at source
5. Encourage a more efficient and environmentally sensitive use of vehicle stock
6. Improve safe pedestrians and all road users
7. Improve the attractiveness of cities for residents, workers, shoppers, and visitors
   (Banister, Unsustainable Transport: City transport in the new century, 2005)

These definitions of sustainability carry common elements in that all revolve around improving urban or even regional, national, and global society through transport services and infrastructure that maximize welfare and economic development while also limiting environmental impact.

3.3 Problem of Unsustainable Transport

The following sub chapter outlines key challenges associated with transportation that inform the development of sustainability analysis tools, as well as a greater understanding of urban sustainability issues. This section outlines some of the key issues addressed in the literature when unsustainable transport is discussed.

3.3.1 Transportation Challenges

Transportation intersects with many segments of society and the environment and can create many benefits for human welfare. It can enable economic growth and connect people to necessary services. However, it can also create a number of challenges. This chapter section outlines a brief overview of some of these challenges, while sections 3.4-3.5 provide greater detail. These sections are not intended to contain every sustainability issue, but to rather provide insight into common issues as discussed within the literature review.

Table 3-1 shares a list of transportation impacts as assembled by Litman & Burwell.

Table 3-1 Transportation Impacts

Economic	Social	Environmental
Accessibility quality Traffic congestion Infrastructure costs Consumer costs Mobility Barriers Accident Damages Depletion of non-renewable resources	Equity/fairness Impacts on mobility disadvantaged Affordability Human health impacts Community cohesion Community livability aesthetics	Air pollution Climate change Noise pollution Water pollution Hydrologic impacts Habitat and ecological degradation Depletion of non-renewable resources

Adapted from (Litman & Burwell, Issues in sustainable transportation, 2006)

This list is used as a starting point for discussion and is intended as a reference for guiding future research into sustainable transportation issues. Before exploring issues with more detail, a common issue described in the literature as a synthesis of many unsustainable transport issues, auto dependence, will first be described.

Vreeker & Nijkamp (2005) suggest that the link between transportation and land use is becoming stronger as transportation is a driver of urban development. However, they also warn that transport can also endanger balanced urban development – a warning which echoes the transport impacts summarized by Litman & Burwell (2006) in the previous table. Vreeker and Nijkamp share common objectives for transport and identify that these may be difficult to balance:

- Economic efficiency – reflected in the increased competitiveness of regions through an improvement in connectivity
- Social equity – reflected in more equal opportunities for better access to transport facilities (for different socio-economic groups, for less central areas);
- Environmental sustainability – reflected in more emphasis on coping with the negative externalities of the transport sector, such as pollution, noise, landscape decay, confection, lack of safety

Adapted from: (Vreeker & Nijkamp, 2005, p. 508)

Vreeker and Nijkamp do suggest that a challenge of these objectives is the integration of new fields and developments into transport planning and reconciling these different interests. These objectives mirror triple bottom line objectives set out in sustainability assessment as well as the transport impacts identified by Litman & Burwell and are a useful set of objectives for further formulating an objective oriented definition of sustainable transport to be used in decision making tools that will be discussed in chapter 4.

3.3.2 Auto Dependence and Sprawl – perspectives on compromised sustainability

Research is pointing to a conclusion that current trends in transportation are unsustainable – when the major definitions of sustainability are applied to transportation and land use patterns there is a pressing need to adopt low carbon solutions for transportation, while also reducing the need for travel (Banister, 2008) (Newman & Kenworthy, 1999). Automobile dependant development is seen as the major issue related to unsustainable transport on an urban scale. While other issues originate from unsustainable transport – such as fuel consumption from increased air travel, the focus of this thesis is on urban transport.

Auto dependence has been discussed at length by Schiller et al (2010) and Newman, and Kenworthy (1999) as a critical issue impacting not just the sustainability of transportation but of cities and indeed society at large. Auto-dependence has been described as a set of transport infrastructure and land use development patterns that favour the automobile and hypermobility that have occurred primarily in North America as well as other parts of the world in the 20th century (Schiller, Bruun, & Kenworthy, 2010) (Newman & Kenworthy, 1999). Schiller et al (2010) write that due to the decreased travel time and increased personal mobility bestowed by automobiles, cities were able to expand greatly with fewer hurdles than when cities were governed by other modes of travel. This rapid growth of automobile focused land use patterns highlights the link between transportation and land use. This growth is most common in North America while in other parts of the world, such as East Asia or Europe, cities are denser and the development patterns are less stratified (i.e.

mixed use) which makes the automobile a less dominant mode (Newman & Kenworthy, 1999) (Banister, 2008) (Schiller et al, 2010).

Auto dependent cities tend to have lower density development patterns, which in turn contribute to increased energy requirements for transportation (Newman & Kenworthy, 1999). Newman and Kenworthy also stress that in the low density auto-dependant cities, such as many cities in the USA, the role of transit and alternative modes is also limited. It is suggested that since automobiles use more energy and create more pollution per trip on average, that this greatly limits the sustainability of these cities.

One issue that is emergent in auto dependent cities that greatly impacts their sustainability is congestion. Congestion is characterized by low traffic flow rate, and high density of vehicles and is a key issue associated with auto dependence. Congestion has been deemed a worldwide phenomenon that is caused by increasing automobile dependence (Moavenzadeh & Markow, 2007). Negative impacts include – loss of economic productivity, increases pollution, and human health impacts.

When a system fails to provide acceptable levels of mobility for different trip purposes and different modes it is considered unsustainable from an economic and social point of view (Banister, Unsustainable Transport: City transport in the new century, 2005). There may also be environmental impacts associated with having a single mode or a single type of user dominating a transport system.

The literature also links auto dependent transport and land uses to social sustainability issues:

- *"If our communities are not walkable or bikeable, we need to drive to schools, shops, parks, entertainment, play dates, etc. Thus we become more sedentary. A sedentary lifestyle increases the risk of overall mortality(2 to 3-fold), cardiovascular disease (3 to 5-fold), and some types of cancer, including colon and breast cancer."* (Cidell, 2012)

3.4 Environmental

3.4.1 Overview of Impacts

In general, transportation consumes resources from the environment for movement – electricity that powers light rail vehicles, gasoline fuel that powers cars, or food that enables active modes of travel all utilize resources to enable mobility. However, the utilization of these resources comes at a cost to the environment. Transportation systems are also considered part of the environment, in that they create a new quality of environment for humans (Low, 2003). As transportation systems interact with, consume environmental resources, and are integrated with the environment, discussing their impacts on the environment is essential for a discussion on sustainable transport. This section of the literature review covers literature on the impacts of travel on the environment.

Transportation is a large contributor to pollution and apart from energy generation and industrial processing, transport is the largest contributor to air pollution (Dobranskyte-Niskota, Perujo, & Pregl, 2007) Environmental impacts can occur in local, regional, or global levels and vary in the magnitude of impact (Rothengatter, 2003).

Many of the impacts discussed will continue to see growth in developing nations, nations undergoing rapid industrial growth, such as China, and nations in transition, such as those in Eastern Europe (Rothengatter, 2003). Rothengatter in 2003 suggests that increases in automobile use, specifically in cities, will lead to continued growth in environmental impacts of transport. A second argument made by Rothengatter is that the impact per trip will also increase as the market share of less environmentally friendly modes may increase, consuming the market share previously held by rail, coach, or other less environmentally impactful modes.

3.4.2 Energy and resource consumption

Private motorized transport, freight, and aviation have consumed and will continue to consume the most resources out of all transport modes. Transportation energy use has been on the rise – over the past forty years it has risen from between 15-20% of all energy use to almost 35% (Potter, 2003). Much of this energy use is automobile oriented – due to the fossil fuel dependent nature of automobile travel (Potter, 2003) (Black W. , 2010) (Newman & Kenworthy, 1999) (Schiller, Bruun, & Kenworthy, 2010). Despite oil being a non-renewable resource, it is unlikely that any shift away from oil will be driven by physical constraints in the near future (Johansson, 2003)

Potter suggests that urban transit consumes very little energy overall (only 4% in the United Kingdom) and has not contributed greatly to this increase. Research has been conducted into systems that provide more energy efficient travel, including work that has shown a general decrease in energy required per trip as density increases (Newman & Kenworthy, 1999).

Energy Security is another issue for discussion. Much of transport relies on fossil fuels that are products with a limited supply (Bongardt, Schmid, Cornie, & Litman, 2011). This limits the long term viability of transport systems as key energy sources can be disrupted or depleted.

Kennedy's study of sustainability in Toronto found that public transit modes attained superior energy performance compared to private auto. Public transit ranged between 0.42 MJ/seat.km and 0.66 MJ/seat.km while automobile ranged from 1.47 to 1.58 MJ/seat.km (Kennedy C. A., 2002). For crush loads, Kennedy reported even greater performance for public transit modes: streetcars 0.17 MJ/person.km, subways 0.10 MJ/person.km and commuter rail 0.33 MJ/person.km.

The following are key issues common to existing transportation systems:

- Current transport systems rely on fossil fuels and are considered energy intensive, violating sustainability principles due to a reliance on non-renewable energy
- Current transport systems are largely focussed on private auto which is not the most energy efficient mode

- A shift to denser urban form, other modes of transport (i.e. cycling public transit), and other technologies can reduce energy use, although there is scepticism about technology shift

3.4.3 CO_2 and Climate Change

Transportation systems are major emitters of greenhouse gases, such as CO_2 that contribute to climate change (Schipper & Fulton, 2003). Bongardt, Schmid, Cornie, and Littman in 2011 stated "overall transportation is responsible for 13% of global GHg emissions and 23% of energy related CO_2 emissions".

According to the US EPA, the average automobile emits 423 grams of CO2 per mile (Office of Transportation and Air Quality United States Environmental Protection Agency, 2011). Various studies have shown that other modes of transport have attained much greater environmental performance, such as Kennedy's study of Toronto where the subway mode achieved 7.7 g C/pkm. However, in the case of Toronto, this can be attributed to a blend of low carbon energy supplying power to the transit system, including Hydro electricity (Kennedy C. A., 2002).

In the literature there is much discussion about the relative performance of different nations on many environmental factors, in particular energy consumption and CO2E emissions. For example Banister (2005) summarizes a steep performance difference in the average emissions per capita in different contexts and associates this difference with different philosophies in planning (car oriented, vs. dense) as well as political outlooks (little climate change mitigation vs. precautions against climate change) . Car ownership is framed as a key driving force for emissions growth, as outlined in the auto dependence sub chapter, with certain nations, namely North American nations, having car ownership and car travel growth rates greatly increasing – at rates higher than that of GDP (Banister, Unsustainable Transport: City transport in the new century, 2005).

3.4.4 Emissions and Pollutants

Transportation systems can produce environmental impacts in the form of air quality emissions. Emissions are often directly tied to energy consumption due to the use of many fuel types (Banister, Unsustainable Transport: City transport in the new century, 2005). These emissions are considered local pollutants because they contribute to a negative local environment. Potter summarizes these pollutants as follows:

- **Carbon Monoxide:** a highly toxic gas, transport is the major source of CO (90% originates from cars).
- **Nitrogen Oxides (NOx):** contribute to acid rain, low level ozone, and respiratory problems. Diesel vehicles are a key source.
- **Hydrocarbons (HCs):** these are known carcinogens.
- **Particulate Matter (PM):** these aggravate respiratory diseases, while PM10 may be carcinogenic.

(Potter, 2003)

Additional emissions that are considered are toxins, which are linked to serious health issues or may be carcinogenic can be considered an environmental and social sustainability issue (Homen & Niemeir, 2003). CO_2 and other greenhouse gases can be considered as emission, however they are not included in this list because within sustainability literature they are often discussed based on the extent to which they contribute to climate change. Greenhouse gases are discussed in 4.4.3.

Environmental policy should be designed to protect against losses, including serious losses of unknown probability, including damage to health due to environmental emissions (Rothengatter, 2003). Legislation exists in many jurisdictions to protect individuals and communities from emissions, such as vehicle emission standards embedded in the Canadian Environmental Protection Act as of September 1999 (Industry Canada, 2011) .

Noise is another key pollutant creating environmental impacts both for humans and ecosystems. For example, transportation systems, including airports, seaports, roadways, and transit systems, all create noise throughout their operations which can have detrimental impacts on human health as well as surrounding ecosystems (Dhingra, Rao, & Tom, 2003) (Hanson, Towers, & Meister, 2006).

3.4.5 Ecological disturbance

A key issue is the physical footprint of transport system (road or railway) that can alter the ecological diversity of a region (Dhingra, Rao, & Tom, 2003). Projects are built in a way that changes the local environment and can create a variety of detrimental impacts to local flora and fauna.

The authors suggest two types of ecological impacts that occur over varying time scales and scopes of human activities:

1. Direct impacts from construction of right of way (roads, railway) and enabling infrastructure
2. Induced development from new transportation infrastructure (Dhingra, Rao, & Tom, 2003)

3.5 **Economic**

The economic dimension of sustainable transport is grounded in understanding how transport contributes to or accelerates economic development (Litman, 2013). On the converse, unsustainable transport can impede transport's role in a healthy economy due to a variety of factors.

3.5.1 Impacts on Economic Activity and Infrastructure Costs

Transportation is responsible for moving goods and people – if a system is unable to do so it will have impacts on the economic viability of a community (Garrison & Ward, 2000). It is also argued that transportation is intertwined with economic development for nations and communities –adequate movement of people and goods is a determinant of the advancement of welfare and economic development (Vreeker & Nijkamp, 2005). In some situations congestion can cause delays that cost economies billions of dollars and limit the overall economic viability of a region or municipality due to workers and goods being stalled (Moavenzadeh & Markow, 2007). On top of congestion, there are additional direct economic costs caused by accidents/collisions (Schiller, Bruun, & Kenworthy, 2010).

A long term impact of unsustainable transport can be an impact on the urban development of a city leading to low density growth – this leads to higher costs to provide populations with necessary services (Newman & Kenworthy, 1999) (Schiller, Bruun, & Kenworthy, 2010). Schiller et al. (2010) also suggest that operating cost recovery is lower in less sustainable cities, meaning that transit systems require more subsidies to operate. Other issues the authors highlight as costs include a loss of useful productive rural land as cities expand.

3.5.2 Pricing of Transport Activities

An economic issue often discussed is the challenge of paying for transportation. Who should pay for which elements of transportation and how? Who should pay for the impacts? Banister writes that at present there is little incentive for drivers to change their behaviour due to unbalanced pricing schemes – drivers pay for none of the environmental costs of their travel so there is very little incentive for them to alter their behaviour (Banister, 2005). The general argument expressed by Banister is common in transportation economics – users often do not cover the costs, direct or the externalities, of their activities. From Banister's argument, which is common in the sustainability literature, it may be essential for users to begin to absorb more of their costs for transport in their activities – including the costs to society and the environment as well as the costs to the economy (such as congestion charges) and the cost of infrastructure. These elements are often seen in sustainability indicator sets as discussed in chapter 4.

3.6 **Social**

Compared to other types of impacts, social impacts are difficult to measure and assessment methodologies are relatively inexact (Sinha & Labi, 2007). However, there has been progress in defining and exploring social impacts – positive and negative – in recent years. This sections explores the social impacts of transportation.

3.6.1 Community, Inclusivity, Equity, and Access

The benefit to welfare of transportation systems are their ability to connect people to other peoples and places (Cidell, 2012) (Vuchic V. R., 1999). However, in auto dependant and unsustainable transportation systems, the creation of equitable and accessible transport is often not achieved. Cidell (2012) describes the case of American transport systems where the lack of personal automobile access leads to a breakdown in accessibility (auto dependence) as a failure of the transport system.

Further, people who are disadvantaged, either economically, socially, or physically should have transport options that meet their needs. A sustainable transport system provides households access to public services, activities, and employments in an equitable fashion regardless of disadvantaged status (EPA, 2011). Conversely, it is also suggested that unsustainable transport systems are ones that do not provide mobility for all and can isolate citizens and exclude them from activities, essentially removing them as active members of society – decreasing their participatory role (Schiller, Bruun, & Kenworthy, 2010).

These issues can also be explored through the ideas of severance - intensive highway development severs communities from one another (Schiller, Bruun, & Kenworthy, 2010). It is argued that these situations decrease interactions between neighbors and can fragment communities and lead to community deterioration - with sprawl, communities can become bedroom communities with little interaction or sense of community (Newman & Kenworthy, 1999). Many of these issues can be related to the types of land use promoted by transportation. While both density and mixed land-use contribute to travel demand.

3.6.2 Health – Injury and Emissions

Due to the above mentioned pollution and congestion, transportation can have negative impacts on human health. Noise and air pollution can decrease quality of environment, causing health impacts on the long term, or have direct impacts via pollutants such as particulate matter (Moavenzadeh & Markow, 2007).

The world health organization sets out standards for air quality to reduce disease and mortality burden due to emissions. Systems that are unsustainable will demonstrate high levels or injury or fatality due to traffic accidents or other road related risks (World Bank, 2002). Transportation can cause serious health issues in the form of physical impairment, injury, and death due to collisions. According to the World Health Organization, each year 1.24 million people are killed in road related incidents and between 20-50 million sustain other injuries (World Health Organization, 2013). Road accidents will likely become the third largest cause of death by 2030.

3.7 Potential Solutions to Sustainability Challenges

3.7.1 Key Concepts

Improving transportation systems to develop a more sustainable system or promote sustainability within an urban area can be achieved through many measures. Moavenzadeh and Markow (2007) suggest the following strategies that are based on learning from multiple contexts:

- **Focusing on demand and supply -** managing demand along with the physical infrastructure's ability to handle passenger demand can create improved mobility and accessibility outcomes.
- **Improving existing transport system performance** – focusing on specific performance measures or features (safety, design features)
- **Understanding the need for trade-offs** – recognizing the sometimes competitive and contradictory nature of policies and objectives can be an essential part of trade-off analysis.
- **Improving management capability** – improving agency or institution management capacity can allow better decisions to be made based on better information.

Source: (Moavenzadeh & Markow, 2007, pp. 10-11)

In this research, trade-off analysis and system performance improvement are key considerations, and will be explored in later chapters in greater depth. It is acknowledged that there is no ‘ideal’ transport system or one size fits all solution and that performance needs to be optimized and that trade-offs will be taken in this process.

In the literature the following mechanisms have been discussed as potential mechanisms for transforming public transit systems to become more sustainable. These techniques have been drawn from a number of sources and can be seen as measures that can be adopted by travellers, institutions, and firms to transform the overall system.

- Travel demand management (e.g. promoting active modes/transit, parking control, promoting behavior change user pricing, congestion pricing.)
- Investment in public transit
- Investment in active modes (biking, walking)
- Policy that combines transportation and land use planning (Transit Oriented Development)
- Promotion of denser mixed land use cities to reduce the need to travel
- Freight management
- Technological innovation (reduced emission engines, Intelligent Transportation Systems)

(Banister, 2005) (Black W. , 2010) (Cairns, et al., 2008) (Garrison & Ward, 2000) (Banister, 2008) (Schiller, Bruun, & Kenworthy, 2010)

Improving the sustainability of a given transportation system is a complex task and there are whole books, papers, and volumes written on each of these subjects. While this thesis is focused on public transit, these ideas are stated here for completion’s sake. Future research which could analyze a city’s transport system holistically could analyze the outcomes produced by these measures, and more, to determine the total sustainability of the system, while this research intends to only analyze public transportation.

Transport policy can be viewed from a number of lenses – even the above mechanisms, which may be seen to benefit certain aspects of sustainable transport have further nuance. The following two sub sections present two further levels of nuance to transport policy to further advance the exploration of sustainable transport and transportation policy.

3.7.2 Distance Reduction – Accessibility vs. Mobility

In the literature a discussion which has been present is between planning for accessibility (ensuring individuals are able to access the services and activities they need) and mobility (predicting and modelling for traffic, without taking into account changes in how people travel) (Cidell, 2012). Cidell and Litman (2013) position these two concepts as paradigms in planning with planning for accessibility being rooted in providing more sustainable transportation and creating a more deliberate and inclusive process that is based on intentional decision making, whereas mobility based planning is founded on the principal of planning systems to meet the growing needs of traffic – for example expanding a freeway to meet the ever increasing demand of traffic.

Litman (2003) defines mobility as measuring the movement of goods and people and suggests that a mobility paradigm is grounded in the idea that any increase in travel is a benefit to society (Litman, Measuring Transportation, 2003). Litman suggests that this paradigm and the policies that fall under it see constraints to physical movement as key issues or problems to be solved and have therefore historically favoured freeways and auto modes, although transit has been integrated as well. As a result, active modes have suffered, suggests Litman.

Accessibility, in this context, is defined as an approach to enable individuals to reach opportunities (destinations, goods, or services) (Litman, Measuring Transportation, 2003). Litman has framed this planning approach as one that considers mobility issues (removing barriers to travel) but also the land use elements of people’s ability to access services. To that end, it is a more integrated planning paradigm and does not carry the inherent biases to the auto mode, freeways, and ultimately auto dependence that mobility centric planning policies do (Litman, Measuring Transportation, 2003).

These two perspectives can be used to understand sustainability policy with interesting nuance. For example, a plan to expand a congested freeway may decrease sustainability through disruption of habitat, increase of emissions, and risk of injury. An alternative rail link may not carry the same extreme sustainability disruptions, however there are still emissions from travel and land use disruptions from construction. Both are under a mobility paradigm and an astute sustainability analyst would ask the question: would an accessibility oriented policy that shifts the demand through integrated land use and transport policies provide better sustainability outcomes? This is just a thought experiment and is not intended to provide an answer either way, but outlines the difference between both paradigms and their implications on policy.

3.7.3 Push and Pull / Stick and Carrot Policy Lenses

In transportation policy formulation, especially in the discussion of measures to direct transport behaviour, two terms are often used to describe policy: push and pull. This binary set of terms can be a useful set in analyzing different types of policy as well as formulating research in the sustainable transportation arena. These terms are briefly summarized here for use in case study discussions.

- Push measures are described as measures that direct individuals away from a certain behaviour - in the case of auto transport, research has found that these types of policies may be less favorable to the public (Eriksson, Garvill, & Nordlund, 2008). Work by Eriksson et al. (2008) as well as Schuitema et al .(2011) are examples of studies that attempt to understand the fairness and public acceptability of push measures such as pricing.
- Pull measures, on the other hand, are measures intended to attract individuals towards an alternative behaviour and away from a less ideal behaviour and may

be seen as more fair compared to push measures (Pridmore & Miola, 2011). Pull measure examples could include improving public transit or cycling infrastructure.

Similar to the accessibility-mobility paradigm, these two concepts can be used to understand sustainable transportation policy. Neither is superior in every given context and should rather be used to analyze or develop policy and conduct research and develop the greatest sustainability benefits. These terms are often used in transport demand management related research and policy and further discussion can be found in that subject. As this thesis focuses on public transit and understanding its benefits, its research can be thought of as a pull measure, however often times public transit corridors do interact with other modes and public transit can be both a push and pull factor.

3.8 Public Transit

3.8.1 Why Focus on Public Transit and Sustainability?

Before addressing sustainable transportation, this section of the literature review will provide basic concepts on public transit systems. For the intents and purposes of the research mass transit systems are considered as a subset of public transit systems that are focused on the delivery of rapid mobility for large quantities of passengers in an urban setting.

Public transit's benefits exist outside of the realm of direct transport service – for example, the Canadian Urban Transit Association (CUTA) estimates that there is a $10 billion benefit to the Canadian economy each year due to transit (Canadian Urban Transit Association, 2010). Littman and Burwell in 2007 suggest that in the past, planning has focussed on providing improved service for the fastest or newest mode, which has led to an automobile focused paradigm. Sustainable transport planning focuses on providing the most ideal strategies that do not necessarily mean faster travel (Litman & Burwell, Issues in sustainable transportation, 2006). Further, transit can provide energy efficient transport in an urban setting that competes with the speed of private automobile travel (Schiller, Bruun, & Kenworthy, 2010). Given the link between energy consumption and pollution, this positions the study of transit as a key provider of sustainable mobility.

Schiller et al (2010) also write on the space efficiency and social benefits of transit across a suite of sustainability criteria and conclude that transit can be a key factor in reducing auto travel and auto dependence in cities. Banister also suggests that a mode shift to transit can achieve sustainable development and urbanization goals, however this mode shift must be accompanied by a reallocation of the public space that was once used for auto travel (Banister, 2008).

Newman and Kenworthy discuss a concept of 'Transit Leverage' – the notion that substituting a transit trip with a car trip has great benefits for the transportation system – in general replacing a car trip with a transit trip greatly reduces the passenger km travelled by that individual. They articulate four major points that support transit as a key transportation intervention for promoting sustainability in cities:

- Good transit options cause businesses and people to adjust their location behaviour
- People who take transit combine trips into single trips – rather than separate car trips (reducing the total number of trips)
- Households that use transit give up a car
- Transit users often use walking or cycling to get to stations or stops

There is great optimism in the literature reviewed for this thesis that public transit has a profound role to play in improving the sustainability of cities and society. Given the potential expressed by past work there is a need to better articulate the sustainable transportation performance of public transport. This thesis focusses on public transit to better understand the sustainability benefits of public transit systems under a sustainable transport lens to aid in local decision making.

3.8.2 Defining Transit – Characteristics and Modes

Public transit systems are often characterized by a predominant mode or technology that is utilized along with sets of operating criteria. Throughout the literature a varied set of criteria are used to quantify the performance of transit, its impacts on a society, the economy, and the environment, as well as the inputs required for successful operation. These criteria and mode are used to characterize transit systems.

As this study is oriented around comparing the performance of different predominant modes for mass transit under sustainability criteria, these terms are necessary and useful.

Modes are an important starting point for the study of mass transit. There are often four predominant modes of mass transit or mass rapid transit that are described in the literature: busways/bus rapid transit (BRT), light rail transit (LRT), metros/heavy rail (HR), and sub-urban rail or regional rail. (Halcrow Fox, 2000). Although, as this research is only concerned with urban transit, suburban rail will not be a focus.

Vuchic (2005) provides useful criteria to classify and describe public transit systems. One of these is a descriptive set of right of way definitions. Right of way is the space in which transit operates and Vuchic has set up three classifications which have seen acceptance in the literature, including seminal sustainable transportation works such as Schiller, Bruun, and Kenworthy (2010). These classifications are:

- **Category A**: transit service has full control over right of way, no access by other vehicles – it can be a tunnel, elevated right of way, or at grade.
- **Category B:** the right of way is longitudinally physically separated from other traffic but has crossings at intersections.
- **Category C:** the right of way is on surface streets with mixed traffic.

(Vuchic V. R., Urban Transit Operations, Planning, and Economics, 2005)

Arguably, right of way is one of the largest determinants of transit performance (Schiller, Bruun, & Kenworthy, 2010). Schiller et al (2010) suggest that right of way can be related to the type of city a transit system serves – the larger the city the more essential it is for a higher right of way. For example, right of way B can be used to add increased efficiency to congested transit systems, improving ridership.

LRT has multiple configurations and operating parameters. Vuchic defines LRT as – "Electric rail vehicles, usually articulated in one to three-car trains operating mostly on ROW category B but also A (e.g., tunnels) and C (in pedestrian zones). The wide range of designs goes from tramway-type lines with priority treatments to small size rapid transit" (Vuchic V. R., Urban Transit Operations, Planning, and Economics, 2005). According to the Light Rail Transit Association there are 556 light rail type systems operating in the world - including light rail, tramways, and electric light railways (Light Rail Transit Association, 2013). However, this research is only focussed on urban systems designed to provide mass transit, which would exclude street car and suburban or interurban systems included in that count.

Figure 3-1 Calgary C-Train LRT

The Calgary C-train is an example of an LRT that operates at right of way A and B.

Heavy rail, rail rapid transit, or metros are rapid transit using rail technologies and are typically defined by their grade separated right of way (Vuchic V. R., Urban

Transit Operations, Planning, and Economics, 2005). According to the World Metro Database, there are 188 metros as of 2013 (World Metro Database, 2013).

Figure 3-2 Heavy Rail Systems in Tokyo

Tokyo features a variety of urban heavy rail systems that are elevated and underground (right of way A), providing high capacity service.

Bus Rapid Transit (BRT) or busways are mass transit systems that are “generally segregated sections of roadway within major corridors, with horizontal protection from other traffic, and priority over other traffic at junctions, which are generally signalised.” (Halcrow Fox, 2000). Similar to LRT, there are many different configurations for BRT or busway type systems. One definition, which encapsulates much of the discourse on BRT is that BRT systems are improved bus systems designed to emulate the performance of rail systems using buses and may include a number of features including pre-paid boarding, high frequency high capacity service (10 seconds in highest performance cases), specialized stations, and higher quality vehicles (ITDP, 2007) (Spencer & Wang, 1996).

The distinction between BRT and busway varies depending on literature; however the term busway is often applied to BRT type service with separate right of way. Spencer and Wang (1996) suggest that in order for a busway style BRT system to achieve true rail level performance it must have a variety of features including: off bus ticketing, signal priority, and overtaking lanes at stops to prevent queuing as well as to allow express bus passing among other design features. According to brtdata.org there are 156 cities with operational BRT systems as of 2013 – although, given the diversity of design features in BRT, it can be argued there is a high degree of variability in performance between these systems. Recent studies of BRT have been descriptive of existing systems, such as Menckhoff's (2005) review of Latin American BRT systems that focussed on system characteristics including length, stops, feeder buses, passenger volumes, and costs.

There are a variety of propulsion systems for buses which may be adapted for bus including diesel, hybrid-diesel, electric battery, biogas, biodiesel, and compressed natural gas. According to the brtdata.org dataset diesel, methane, and compressed natural gas (CNG) have been reported as BRT fuels, however most agencies have not reported a fuel type (EMBARQ, 2012). Alternative fuels, such as biogas, may offer reduced environmental impacts and improved financial benefits (Baltic Biogas Bus, 2012). However, the technology is still new and has yet to be implemented on a wide scale or in BRT style operations.

Figure 3-3BRT – TransMilenio, Bogota

TransMilenio features many high performance BRT features including separate right of way (typically B), off bus ticketing, and passing lanes. These features enable it to achieve high hourly capacities. Picture credit: flickr user mariordo59

http://www.flickr.com/photos/30998987@N03/8434093080/in/set-

3.8.3 A Review of Modal Comparison

Comparative system performance has been a major topic of inquiry in order to understand how well individual systems perform compared against others, or how well certain modes perform compared against other modes. For example studies of the maximum capacity individual systems have been able to achieve as well as how quickly systems are able to move passengers has been a topic of inquiry (Thilakaratne R. S., 2011). To date many studies have compared public transit modes based on the inputs required to construct and operate, as well as their impacts on the environment and urban form as well such as Hensher (2006), Puchalsky (2005), or Fels (1974).

For this thesis inquiry the focus is on comparing the relative sustainable transportation benefits of each system type, which could be considered as a synthesis of these efforts. Past studies have compared mass transit modes on specific parameters, such as emissions or energy consumption (such as Fels (1974) or Puchalsky (2005)), or focussed on specific geographic contexts – such as the study comparing light rail or busway in Beijing by Spencer and Andong in 1996. However, as an older study this study's main focus was on loadings and costs – a comprehensive sustainability analysis would include other considerations.

Vuchic's work covering planning public transit in two major texts, Urban Transit Systems and Technology (2007) and Urban Transit Operations, Planning, and Economics (2005) both provide insight into the planning, development, and implementation of transit systems as well as the performance of transit systems. A variety of indicators and methods to assess performance are put forward as well as demonstrated for theoretical systems and operational systems. These works are foundational for transit studies and summarize the key concepts in transit analysis and planning.

Vuchic classified modal comparison studies in terms of four types:

I. Theoretical comparisons of typical modes in a hypothetical area
II. Analyses of general characteristics of different modes
III. Comparison of different modes serving similar areas
IV. Comparison of different modes planned for a given area

(Vuchic V. R., Urban Transit Operations, Planning, and Economics, 2005)

This break down can provide great insight into formulating a multimodal sustainability study, as well as reviewing past studies. Vuchic suggests that studies should focus on the complete mode as costs are often incurred in developing the right of way that serves the mode, and not the technology (i.e. the bus or type of light rail vehicle) itself.

Many recent studies have focussed on the comparison of a newer form of rapid transit, BRT, with heavy rail and light rail transit. Research has shown there is growing support for BRT or bus way systems as an alternative to heavy rail and light rail modes by offering comparable service at a lower cost (Hensher, Sustainable public transport systems: Moving towards a value for money and network-based approach and away from blind commitment, 2006). BRT planning guidelines state that a typical BRT system can cost 4 to 20 times less than an LRT system and 10 to 100 times less than a metro, which has found it to be an ideal mobility solution in low income nations as well as jurisdictions seeking economic efficiency (ITDP, 2007). However, these studies do not provide a large sample of BRT projects or specific reference to the operating conditions necessary for corridors to provide this high capacity service.

Hensher (2006) cites the TransMilenio system's (in Bogota) capacity of 38,000 as an example of a high capacity BRT system. However, research has shown that bus technology creates greater emissions per passenger km travelled overall compared to LRT and that these emissions are localized, which raises questions about the environmental benefits of this technology (Puchalsky, 2005).

Spencer and Andong (1996) completed an early study comparing BRT and LRT based on theoretical plans for Beijing. The paper also included a "skytrain" alternative that would operate similar to a metro or heavy rail system, only with reduced capacity. The alternative has a separate right of way that is elevated (ROW A) and uses smaller vehicles. Through analytical modelling, the paper provided a comparison based on running time, provided capacity derived from vehicle capacity and headway, and ultimately cost/benefit. The paper found that for the alignments considered, the bus way option provided the greatest cost/benefit performance, however there were limitations to the study such as a lack of user perspectives and environmental considerations.

While the paper is framed as a comparison of BRT, LRT, and skytrain technologies, the paper can also be considered as a comparison of specific scenarios and conditions that were framed based on benchmarks from other BRT and LRT case studies (as well as a skytrain plan drafted for Beijing) which is an important consideration when investigating modal comparison.

Another perspective on modal comparison has considered performance in a progressive nature – from low velocity and capacity to high capacity (Thilakaratne R. S., 2011). This outlook considers gradual development of a corridor based on the demand for travel and need for mobility starting with local service, and gradual moving through express bus, BRT/bus way, LRT, and eventually to metro.

Bruun, in Schiller et al. (2010) provides research into the relative performance and costs of major rapid transit modes. Similar to Puchalsky, local pollution is reported as a disadvantage of BRT, along with noise levels. The increase of operating speeds and capacity reported by Bruun follows a BRT→LRT→ HR (also noted as Metro and Rail Rapid Transit) progression (Schilleret al, 2010). All values are reported for 'wealthy nation standards' meaning operational configurations and level of service that are experienced in developed nations, which may differ from the low and middle income nations that other BRT data are reported from. For example, Schiller et al. (2010) report that in some Latin American or Asian countries there may be a higher tolerance for crowding than in North America. Capacity achieved on one bus line or system is often not a function of the mode, but rather numerous factors associated with the overall system layout (Vuchic V. R., Urban Transit Operations, Planning, and Economics, 2005).

However, Vuchic (2005) does provide a theoretical progression of capacity based on increasing vehicle size parameters, headways (minimum and maximum) , operating speed, and capacity ratios which shows a similar progression from standard bus(single stop) → articulated bus → (single stop) → mixed stop 50% standard 50% articulated → High Capacity Bus → Street Car ROW C → LRT ROW B → Automated Guideway Transit (several options are presented) → RRT (several options are presented) → Regional Rail (diesel) → Regional Rail (electric). As these options are theoretical, there can be some exceptions based on system configuration; however they do provide some interesting points of discussion for the relative baseline performance of different types of public transit systems.

Bruun from Schiller, Bruun, and Kenworthy (2010) reports price ranges for vehicle costs, indicating BRT vehicles cost $500-$1,500 thousand, LRT $2.5-$3.5 million, and RRT $2-$3 million. These figures are aligned with the lower capital cost for BRT notion provided by Hensher (2006); however they are focussed on vehicles only, not right of way. Operating costs are provided as well, indicating that RRT is cheaper than LRT per vehicle mile ($7-$13 dollars, compared to $7-$18) however BRT costs are provided in vehicle hours, and no direct comparison can be made.

The thesis by Thilakaratne (2011), based on data from transit systems from a variety of global contexts, stratifies the mobility performance of major transit modes. This stratification can raise questions to the claims by Hensher (2006) and ITDP about the performance equivalence of BRT/Busway systems to LRT and Metro. While the data from the thesis study shows that the highest performing busways can achieve 25,000 passengers per hour per direction in capacity, which is greater than the 18,892 reported for LRT the general trends reported in the study indicates a general progression of modes within a corridor. The reports by Hensher and ITDP are based on the highest performance systems, such as TransMilenio in Bogota which utilize large right of ways and have established demand, so comparable performance may not be as commonly attained. This raises the question of case by case analysis, vs. the use of best in class benchmarking.

Another study by Agarwal and Zimmerman (2008) that reports the sustainable mobility experiences of Urban India views modal comparison in a different light. The authors frame the discussion not necessarily of capacity, but in terms of city factors and what sort of trips are being served by the system. Metro is described as a useful system type for dense cities with linear travel corridors, whereas a bus system may be more suited for cities that are lower density and are multinucleated (Agarwal & Zimmerman, 2008). This discussion adds further nuance to the modal debate.

Another comparison between modes was completed by Rahman in 2009, this major study focussed on estimating the entire lifecycle energy requirements for both BRT and LRT. Ottawa, Canada was used as a case study and vehicle and infrastructure energy usage were considered (Rahman, 2009). From the study it was found that energy consumption is very context specific and depends on system configuration, however in a non-tunnel running configuration LRT consumes approximately 12% more energy than BRT over the entire lifecycle, while with a tunnel configuration the energy intensities are similar. The study also found that indirect energy accounted for 66% of the total energy consumed.

Table 3-2 provides a summary of performance issues related to planning and operating LRT, BRT, and RRT/Metro systems.

Table 3-2 Modal Comparison Summary

	BRT	*LRT*	*RRT/ Metro*
Line Capacity (pers/hour)	*9,000-30,000*	*10,000-20,000*	*11,000-81,000*
Maximum gradient	-	*6-9% (observed 15%)*	*3-4% (rubber 7%)*
Capital Cost(millions $)	*0.5-55*	*6-37.8*	*23-350*
ROW	*C,B,A*	*B or A (C for street car style operation)*	*A*
ROW Requirements	*Variety of conditions, separate right of way for peak performance*	*Variety of conditions, separate right of way for peak performance*	*Separate right of way, tunnelled or elevated are most common*
Vehicle Capacity, vehicles per train	*160(max)*	*110-250, 2-4*	*140-280, 4-10*
Operating Speed(km/h)	*15-25*	*18-40*	*25-60*
Frequency (trains/h)	*120-300*	*40-90*	*20-40*
Environmental Impacts	*Medium noise and air pollution, generally safe for passengers*	*No localized pollution, generally safe for passengers*	*No localized pollution, generally safe for passengers, more noise than LRT*

(Vuchic V. R., Urban Transit Systems and Technology, 2007) (Wirasinghe, et al., 2013) (Deng & Nelson, 2010) (Siu, 2007) (Schiller, Bruun, & Kenworthy, 2010) (Wright, 2004) (United States General Accounting Office, 2001)

3.9 Conclusion

In the literature there is a common practice of comparing individual technologies based on specific case studies or specific indicators or characteristics of transit. Research by authors such as the Spencer and Andong (1996), Puchalsky (2005), Fels (1974), the ITDP (2007), Agarwal and Zimmerman (2008) greatly inform or expand the knowledge base of transit and have developed a foundation for further research and systems planning. However, thus far there has not been enough research that compares entire transit systems and their ability to provide sustainable mobility. As noted in the introduction, there are studies into indicator sets and studies that apply individual indicators or select indicators but few studies have compared modes or systems holistically – this positions this research quite well among the continuum of public transit research.

While the studies above are able to highlight differences, weaknesses, and strengths that may be generally applied to technologies or modes there is a gap in the literature for covering transit from a sustainability lens that combines these perspectives along with other sustainability criteria. There is no one set of characteristics for any one mode, but rather a diverse set of characteristics shaped by the context the system is delivered in (Vuchic V. R., Urban Transit Systems and Technology, 2007)

Chapter 4: Sustainable Transportation Assessment

4.1 Chapter Overview

A specific literature review in sustainability analysis as it pertains to transportation analysis was also conducted in order to inform this thesis project. This chapter contains this literature review as well as commentary on the papers, theses, and reports utilized for it. Section 4.2 provides a scope for this literature review while Section 4.3 provides an overview of the literature used on decision making methodologies and then provides analysis on the key methodologies used for this thesis' guiding research questions. Section 4.4 contains a summary of the literature review on the use of indicators, metrics, and indices for sustainable transportation research as well as survey of papers that covered the subject from a more general basis. This section also provides tables of commonly occurring indicators in the literature and commentary on the frequency and use for the analysis of sustainable transportation. This literature review seeks to find indicators that will be useful for the comparison of systems under sustainable transportation criteria. Techniques used to create indices, normalize indicators, and select indicators are also covered within this section. Section 4.5 contains a review of key studies of sustainable transportation that informed this thesis research. Finally, section 4.6 provides concluding comments on the literature review and what can be applied for this particular study.

4.2 Literature Review Scope

This section of the literature review is focussed on understanding the current state of research into sustainable transportation analysis by exploring sustainable transportation studies and research focussed on two areas:

- The development of effective indicators, metrics, and indices to quantify and measure sustainable transportation
- Past studies of sustainable transportation that have either applied indicators, metrics, and indices, or have utilized another technique to measure sustainable transportation

The literature review surveyed papers, theses, reports and texts from a variety of fields including civil engineering, environmental science, economics, urban planning, and geography.

4.3 Transportation Decision Making Methodology

4.3.1 Overview of Literature

The field of public transit performance analysis has an established literature base of theory and applied studies that have analyzed the performance of transit under a variety of lenses including efficiency, effectiveness, economic performance, and environmental impact. In the twentieth century, as larger data sets became available to study existing systems, larger studies could be conducted and more research was undertaken. Early studies were concerned with operating parameters of transit systems, such as operating expense per passenger, and were developed to understand economic efficiency(e.g. revenue vehicle miles per vehicle) or to understand vehicle utilization. Vreeker & Nijkamp (2005) suggests that transport planning problems have a degree of complexity that requires the application of both theory and practical policy. As research in transit and other fields has developed considerably in the late 20^{th} and early 21^{st} this literature review will survey key contributions from a variety of authors and fields to aid in the development of sustainability research that will build upon previous transit research from fields of theory and practice.

4.3.2 Sustainability Analysis

As previously discussed, sustainability has emerged as a key set of practice and research over the past two decades amongst a backdrop of increased awareness of sustainability issues, improved analytical tools, and increased interdisciplinary research endeavours. Most sustainability assessment research utilizes tools for a variety of fields in order to look at issues from multiple perspectives (for example, triple bottom line) and in a holistic light.

Various high level frameworks have been developed and considered in the literature, in policy, and in practice. Jeon and Amekudzi (2005) conducted a thorough review of sustainability analysis as well as definitions of sustainability and tools commonly used.

The authors have broken sustainability frameworks into the following categories based on terminology commonly used in the literature:

- **Linkage based frameworks:** tools that attempt to utilize indicators and metrics to understand particular conditions affecting sustainability and the impacts of these conditions as well as what actions can be taken to address them.
- **Impacts based frameworks:** tools that focus on the impacts of actions/projects/plans on the sustainability of a particular system being analysed or considered. Three dimensional frameworks (i.e. economic, social, environmental) fall under this category.
- **Influence Oriented Frameworks:** tools that categorize indicators or metrics based on their level of influence and the control that the responsible agency has over them.

(Jeon & Amekudzi, 2005)

The authors share that regardless of the framework used, effort should be taken to balance the use of inputs and outcomes or impacts as measures of transport sustainability. Jeon and Amekudzi (2005) also suggest that these frameworks can be synthesized or integrated in order to ensure agencies have the right analysis and indicator system.

Pope, Annadale, and Morrison-Saunders (2004) describe sustainability assessment as a process of exploring the implications of existing policies, plans, programmes, projects, or pieces of legislations, or existing practise or activities on sustainability. The authors suggest that while there are many attempts to assess sustainability, many could be declared as extensions of an EIA framework, that reflect a triple bottom line conception of sustainability, but do not necessarily truly contribute to sustainable practice (Pope, Annandale, & Morrison-Saunders, 2004). The authors suggest that most definitions and approaches to sustainability assessment are generic and describe a suite of processes and that more rigorous approaches are necessary to truly use assessment to promote sustainability.

Analysing and planning transport systems relies on indicators to understand trends and model or analyse impacts (Sustainable Transportation Indicators Subcommittee , 2009). The Subcommittee also suggests that comprehensive and balanced indicator sets should include indicators from all major categories of issues in order to improve the decision making framework. Littman and Burwell (2006) suggest that conventional evaluation techniques used in transportation analysis mostly consider motorized travel and may not fulfil sustainable transport objectives – meaning there is a need for expanded indicators and methodologies for sustainability analysis (Litman & Burwell, Issues in sustainable transportation, 2006).

Sustainability in transport is a widely acknowledged necessity due to triple bottom line impacts - indicators allow impacts of transport to be recognized and measured and can be used as a basis for policy making (Bongardt, Schmid, Cornie, & Litman, 2011). While there is much discussion on indicators and their application, a paper found that few studies use sustainability indicators to compare systems (Haghshenas & Vaziri, 2012). While studies are emerging that are applying 'holistic' sustainability analysis, such as Haghshenas and Vaziri (2012), Jeon (2007), and Kennedy (2002), all of which focus on different elements of transportation – ranging from macroscopic analysis of cities (Haghshenas and Vaziri), to a detailed analysis of one city (Kennedy). While these studies contribute to a much needed hole in the research, they do not focus explicitly on transit and how transit performs under sustainability criteria. There is a current deficit of major studies that have compared a wide range of transit systems using comprehensive sustainability analysis. This study aims to contribute to this gap by comparing transit systems, however, first a review of indicators and sustainability analysis techniques is required.

Ramani et al (2011) proposed a general sustainability assessment framework for transport agencies along with a review of key sustainable transportation concepts. This framework presents a 5 step process, with feedback loops between each level of the process. The five components of the process are:

- understanding sustainability
- transportation sustainability goal development
- development of objectives
- development of performance measures
- performance measure application

While this study is assessing projects from the lens of an agency, it seeks to develop a useful analytic tool so this 5 step process is applicable to this research. Indeed, the literature review portion can be seen as covering the understanding of sustainability as well as the development of goals, objectives, and performance measures while chapter 6 is the application. This general framework is a foundation case for which sustainability studies and analyses can be based upon.

Vreeker & Nijkamp (2005) suggest that given the complexity of transportation planning and the increasingly multidimensional nature of the problems encountered by transport planners and those engaged in transport planning, a new set of tools is required to effectively tackle these challenges. Traditional approaches of simply analyzing a particular indicator or performance measure does not capture the richness, complexity, or competing objectives that sustainability issues may present which requires a different tool – multi criteria decision making.

4.3.3 Analysis and Decision Making Across Multiple Dimensions

Key sustainability studies including work by Jeon(2007), Kennedy(2002), Castillo and Pitfield (2010), and Haghshenas & Vaziri (2012) as prime studies in the literature to consider sustainability analysis as a problem with multiple dimensions or criteria. These studies utilize analysis that break down various aspects of sustainable transport into sets of criteria or accounts of analysis and evaluate these criteria/accounts in order to understand the sustainability implications of the system or problem being explored. Vreeker & Nijkamp (2005) provides a primer on using multicriteria evaluation for transport policies and problems. Other studies have utilized analytical modelling outputs and frameworks of wellbeing for individuals and whole communities to inform sustainable transportation (Johnston, 2008). All these studies are focussed on exploring sustainability through multiple dimensions. From both a theoretical and practical lens, the applicability of multi criteria tools for sustainability analysis is well established and will further be explored in this sub chapter.

Throughout the literature, Multi Criteria Analysis (MCA) and Multi Criteria Decision Making (MCDM) are common types of tools utilized in sustainability analysis, both within the transportation field, as well as in other disciplines. In both research and practice, a variety of MCA/MCDM types of tools have been used in studies that have influenced this thesis. Evaluating transportation projects using multiple criteria, as opposed to a single criteria enables a more holistic analysis as well as the perspectives and concerns of multiple stakeholder groups to be considered (Sinha & Labi, 2007). Whereas fixed or “rigid evaluation techniques” may encounter issues of not covering all issues necessary in the planning environment, multi criteria techniques offer the opportunity to explore and account for a variety of issues (Vreeker & Nijkamp, 2005). Vreeker & Nijkamp suggest this reduces bias in decision making.

Jansen and Munda from Vreeker and Nijkamp (2005) provide a system to classify MCA methodologies based on four distinctions. This system is shown in Figure 4-1.

Figure 4-1 Classification of MCA Approaches

1. The set of the alternatives: discrete versus continuous problems. In evaluation practices, a distinction is often made between discrete and continuous problems. Discrete decision problems involve a finite set of alternatives. Continuous problems are characterized by an infinite number of feasible alternatives.
2. The measurement scale: quantitative versus qualitative attribute scale. Some problems include a mixture of qualitative and quantitative information. Qualitative and mixed evaluation methods can handle this type of information to analyze alternatives.
3. The decision rule: price or priorities. The decision rules is unique for each method. Priorities used in MCA reflect the relative importance of the criteria considered in the analysis. In CBA, prices are used to calculate benefit-cost ratios. These prices are derived directly or indirectly from market prices or are assessed by means of various valuation methods.
4. The valuation functions: standardization versus valuation. In order to make score comparable, they must be transformed into a common dimension or into a common dimensionless unit. This can be done by transforming the scores into standardised scores by means or a linear standardization function, or by using value or utility functions. Utility and value functions transform information measured on physical measurement scales into a utility or value index.

Adapted from (Vreeker & Nijkamp, 2005, p. 513)

These core principles for characterizing MCA approach can also be utilized in structuring and designing an analytical process. Vreeker and Nijkamp also outline three approaches to applying MCA in making decisions: utility or value approaches, programming methods, and outranking methods.

In utility and value approaches, the problem is turned into an optimization problem where the multicriteria problem is reduced to a uniciterion optimization problem based on a hypothesis that a value or utility function can be defined for the decision problem and the alternatives being considered (Vreeker & Nijkamp, 2005). The authors draw attention to the distinction between multi attribute utility theory (MAUT, which requires the computation of an expected utility for each alternative) and multi attribute value theory (MAVT, which draws upon a value function to represent outcomes) functions – utility functions may be value functions, but value functions may not be utility functions. They state that in MAUT and MAVT the decision makers are involved in a two-step process – 1) developing functions for each criteria and 2) calculating the expected utility of the aggregated utility functions.

Vreeker & Nijkamp (2005) also outline the programming method, multi-objective programming (MOP), which aims to reach a set of goals that are predefined maximizing or minimizing objectives. MOP works to find feasible solutions and divide them into efficient and inefficient solutions - the decision maker may then chooses the best solution from the most efficient solution set (Vreeker & Nijkamp, 2005).

Finally, the authors also explore outranking methods, which is also called the French School. This technique does not develop a mathematical model that represents the decision maker's preferences, but rather directly compares alternatives.

As suggested by its application in past studies, MCDM is a useful tool for sustainability analysis as sustainability calls for an approach where multiple issues may be evaluated at once (Jeon & Amekudzi, 2005). This tool has fit into the transport analyst and researcher's tool box in a useful way beyond sustainability for just this reason – where as other tools are tailored for specific issues (i.e. monetizing GHg emissions or noise) MCDM allows a more holistic view of problems and perspectives to be integrated into the decision making process (Sinha & Labi, 2007).

While there are no absolute definitions for MCDM, a common definition is that MCDM is a tool used to improve decision making by balancing multiple objectives explicitly (Zeleny, 1982). Gwo-Hsiung and Jih–Jeng (2011) set out 5 steps to consider when developing MCDM decision making processes:

- Step 1: "Define the nature of the problem;"
- Step 2: "Construct a hierarchy system for its evaluation;"
- Step 3: "Select the appropriate evaluation model;"
- Step 4: "Obtain the relative weights and performance score of each attribute with respect to each alternative;"
- Step 5: "Determine the best alternative according to the synthetic utility values, which are the aggregation value of relative weights, and performance scores corresponding to alternatives."

  (Gwo-Hshiung & Jih-Jeng, 2011, p. 15)

This process is utilized in chapter 5 to develop decision making and support tools, as well as to conceptualize sustainability as a multi criteria problem. This is a brief treatment of MCDM, however the discussion is continued in the review of past studies and this is intended as an introduction to the subject. Its application, in particular issues on weighting, defining the nature of the problem, and selecting alternatives, are discussed in length in chapter 5 and 6, and also in subsequent chapter 4 sub sections.

4.4 **Sustainable Transport Studies**

4.4.1 Overview of Past Studies

Key studies were utilized to inform this research into sustainability analysis including Kennedy's Comparison of the Sustainability of Public and Private Transportation Systems: Study of the Greater Toronto Area (2002), Jeon, Amekudzi, and Guensler's Evaluating Plan Alternatives for Transportation System Sustainability in the Atlanta Metropolitan Region (2009), and Haghshenas and Vaziri's Urban Sustainable Transportation Indicators for Global Comparison (2012).

Vincent and Walsh’s The Electric Rail Dilemma(2003), and Puchalsky’s Comparison of Emissions from Light Rail Transit and Bus Rapid Transit (2005) were reviewed as papers that demonstrated comparisons of modes and systems based on environmental criteria, while also highlighting useful techniques and resources for sustainability analysis. These papers are discussed throughout the thesis and are not mentioned here.

4.4.2 Review of Past Studies

Kennedy’s 2002 paper is classified as a modal comparison study as it is an in depth comparison of private and public transportation in the Greater Toronto Region. This study greatly contributes to the field of sustainability analysis by conducting a holistic triple bottom line comparison of the benefits and negative impacts of private and public transport within a fixed geographic area. A set of indicators are set out and data is collected that combined historical sources with analytical models or estimates where appropriate to conduct a rigorous analysis. Unlike the other two studies mentioned in this section, there is no effort made to aggregate the data collected or the indicators used for composite indicators or indices, however, the results are clearly explored through in depth analysis.

The analysis finds that there are benefits to both types of travel for the Toronto region due to the level of sophistication in analysis and the number of indicators used. As there are multiple indicators under each category, the potential trade-offs, costs, and benefits within each sustainability category, as well as within each system can be observed and better understood. The key take away from this study is the general approach to setting out indicators and categories for analysis as well as systems being compared as well as setting a clear scope for analysis.

Jeon (2007) and Jeon et al. (2009) approach for evaluating different plan alternatives presents a methodology for sustainability analysis grounded in MCDM. First, the article provides a literature review of sustainability based in the triple bottom line paradigm, and sustainability indicator frameworks that reviews common frameworks for utilizing indicators in sustainability analysis. A review of MCDM techniques including the history of MCDM in decision making as well as recent innovative developments is also included to provide context for the analysis techniques proposed. These studies stem from the same dissertation, Jeon (2007), focussed on applying composite indicator or index techniques to analyzing sustainability plans in a geographic region to both better understand how different plans perform under rigorous sustainability analysis and also contribute to the state of applying holistic sustainability research to decision making problems.

These studies, henceforth referred to as the Jeon studies, break down sustainability into four categories as an expansion of the triple bottom line framework: environmental, social, economic, and system effectiveness. These four categories measure the impacts of different plan alternatives on the city and transportation system, as well as those who live there. Two alternative transportation-network-land use scenarios for the Atlanta Metropolitan region were modelled and the outputs with respect to 30 indicators were analyzed and compared to a 2005 base case scenario. These indicators were aggregated into indices by sustainability category and then into a composite indicator based on single attribute utility functions. Weighting for these functions were assigned equally at both the composite indicator level as well as the sustainability category level.

Sensitivity testing, which changed the values of weighting, was conducted to demonstrate how different weightings impact the overall composite index value as well. The study demonstrated how to apply a MCDM based decision support tool for sustainable transport analysis, analyzed various indicator frameworks, demonstrated how to calculate composite indicators or indices, and discussed how these tools can be made to explore trade-offs between different elements of sustainability goals.

The key takeaways from the Jeon studies is the methodology of how to use composite indices with a modified triple bottom line framework under a MCDM environment in order to compare the overall sustainability of multiple systems or plan alternatives. This technique can be adapted to for public transit analysis by determining appropriate measures or indicators of public transit sustainability and selecting appropriate data.

The second study that greatly informs this research focuses on the comparison of multiple cities based on their overall transportation systems. Haghshenas and Vaziri (2012) presented a study of cities and their transportation systems from a holistic sustainability lens. Similar to Jeon (2007) and Jeon, Amekudzi, and Guensler (2009) the study utilized an approach grounded in MCDM with different sustainability categories each with a set of factors represented by an indicator. Also similar to Jeon studies, this study utilized a weighted sum equation to create composite sustainability indices for each city. This study utilized the UITP's (International Association of Public Transport) millennium cities database for sustainable transportation, which contains 100 cities, along with environmental, economic, and social indicators to rank all cities in the database based on their relative sustainability performance.

Z scores of all indicators are calculated to normalize all indicators and generate composite indices for each sustainability category as well as a composite sustainability index. Developed Asia and Europe have the best CSI for transportation. The key conclusions of the study were that denser cities tend to have higher composite sustainability results, higher auto share lowers environmental sustainability index, and that urban area has a negative correlation with composite sustainability index.

The overall contributions of the article are oriented around the development of composite indicators using weighed sum techniques, similar to the Jeon studies, as well as basic insight into denser cities having more sustainable transportation systems.

4.4.3 Summary

Each of these studies greatly informs the development of this research and key contributions have been selected from each paper to develop the methodology that will be utilized to assess the sustainability of public transit within this study. The key concepts taken from each study has been summarized in Table 4-1.

Table 4-1 Key Concepts from Sustainability Studies

Author	Key Concepts
Kennedy (2002)	▪ Analyzed two different types of travel in the GTA ▪ Developed clear indicators and use them to explore benefits, costs, trade-offs based on triple bottom line ▪ Developed a rigorous analysis for each area of sustainability
Jeon (2007), Jeon, Amekudzi, and Guensler (2009)	▪ Analysed three scenarios in the Atlanta Metropolitan area ▪ Used 30 indicators based on an expanded triple bottom line to understand trade-offs and costs/benefits as well as to develop composite sustainability index ▪ Normalization based on single attribute utility, weights equally assigned
Haghshenas and Vaziri (2012)	▪ Analysed the transport systems of 100 cities based on a variety of sustainability factors ▪ Used z-score normalization and weights that were equally assigned

4.5 Indicators, Metrics, and Indices

4.5.1 Indicator Selection - Literature Practices

Indicators are used for a variety of purposes including measurement, policy formulation, and project assessment (Joumard & Gudmundsson, 2010)

Performance measures are measurable criteria that are utilized to evaluate progress towards goals (Ramani, Zietsman, Gudmundsson, Hall, & Marsden, 2011). Bongardt, et al.(2011) also suggest that indicators should be used to measure progress, inputs, and outputs of a transport project. Selecting indicators is at the heart of this research project. As there are a large number of indicators for evaluating sustainability and transportation performance, reviewing how past studies have selected indicators or suggest how to select indicators will inform the development of this thesis' indicator framework. As outlined previously, sustainability studies often use a triple bottom line approach focusing on exploring sustainability through a lens of environmental social, and economic issues. In transportation research, sustainability studies also use a similar framework to explore sustainability issues.

In a variety of fields, including environmental analysis of transport projects, indicator selection is the first challenge encountered. (Rothengatter, 2003) This statement can be expanded to all areas which are impacted by transportation. In formulating a study, indicator selection is the first issue analysts often encounter. Understanding the issues being addressed or researched and the right set of indicators can become challenging with a topic as broad as sustainability (see discussion in chapters 2 and 3). It is important to note that the indicators that are selected can greatly influence the results of the analysis (Litman & Burwell, 2006). So great care must be practiced when selecting indicators. Unlike studying the GHg emissions of a roadway, which is a finite problem, there is inherit ambiguity in sustainability and the analysts own biases can be built into the problem definition.

To aid in limiting this bias, best practices, foundational literature, explicit statement of research goals, and past studies can be used in aiding the development of indicator frameworks. Litman (2013) has summarized best practice for indicator selection from a number of authors. Figure 4-2 contains an excerpt from the Litman summary for use in this thesis.

Figure 4-2 Indicator Best Practices

- ***Comprehensive*** – Indicators should reflect various economic, social and environmental impacts, and various transport activities (such as both personal and freight transport).
- ***Quality*** – Data collection practices should reflect high standards to insure that information is accurate and consistent.
- ***Comparable*** – Data collection should be clearly defined and standardized to facilitate comparisons between various jurisdictions, times and groups. For example, "Number of people with good access to food shopping" should specify 'good access' and 'food shopping.'
- ***Understandable*** – Indicators must understandable to decision-makers and the general public. The more information condensed into an index the less meaning it has for specific decisions.
- ***Accessible and transparent*** – Indicators (and the raw data they are based on) and analysis details should be available to all stakeholders.
- ***Cost effective*** – Indicators should be cost effective to collect.
- ***Net effects*** – Indicators should differentiate between net (total) impacts and shifts of impacts to different locations and times.

(Litman, 2013, p. 71)

In their outline of the ELASTIC framework, Castillo and Pitfield (2010) share the following useful criteria for indicator selection based on their research drawn from the field and other literature:

- **Measurability**: "indicators must be measurable in a theoretically sound, dependable and easily understood manner."
- **Ease of availability:** "it should be possible to easily and at a reasonable cost, collect reliable data on the indicator or calculate/forecast the value of the indicator using accepted models."
- **Speed of availability:** "data from which the indicator is derived or calculated should be regularly updatable with a view to ensuring the shortest lag between the state of affairs being measured and the indicator becoming available"
- **Interpretability:** "an indicator and its calculation should yield clear, unambiguous information that is easily understood by all stakeholders."
- **Transport's Impact isolatable:** "it should be possible to isolate transport's share of the impact that the indicator is purporting to measure."
  (Castillo & Pitfield, 2010)

These criteria are useful for selecting and formalizing indicators, however they are specified for the elastic process, specifically to aid with the selection of indicators for the elastic methodology and may not be completely applicable in all analysis frameworks.

Hensher (2005) also provides guidance for the development of performance measures.

- Indicators should relate to the objectives of the organization and include internal and external factors.
- Indicators must be clearly defined and unambiguous – their numeric values or changes in values should be clearly good or bad.
- indicators must distinguish between factors that the organization can and cannot control.

- Indicators must be comprehendible by those who can influence them
- The results from the measure must be related to the overall analysis of performance. “This requires an unambiguous definition of an improvement in performance”

Drawn and adapted from (Hensher, Performance Evaluation Frameworks, 2005, p. 87)

Hensher’s performance measure suggestions are targeted at the development of performance measurement in public and private sector organizations so their inclusion has merit in the development of a tool that has utility in both research and decision making contexts.

4.5.2 Overview of Composite Indicators

As this study seeks to develop a useful tool to analyse sustainable transportation contributions of public transit systems, composite indicators will be utilized similar to past studies. To aid in the study of sustainable transportation, a review of composite indicators is included. The OECD “Handbook on constructing composite indicators: methodology and user guide” was utilized in this study due to its depth of detail, citations in other studies, and the quantity of techniques discussed within it. In addition, two transportation studies that utilize sustainability concepts and composite indicators greatly inform this literature review – Jeon’s 2007 dissertation and the additional articles co-authored by her, as well as Haghshenas and Vaziri (2012). These works are foundational to the application of composite indices or indicators to transportation system analysis for sustainability analysis.

Composite indicators allow comparison of different entities under complex fields and conditions (Nardo M. , et al., 2005). Nardo et al suggest key pros of the composite indicator or index tool, summarized sources, including that they can present ideas easier than sharing several indicators at once, they are useful for ranking entities on complex issues, and are useful communication tools. However the authors also share negative aspects or cons including they also run the risk of misleading policy if they are not carefully constructed or if certain dimensions or indicators are ignored, and can be misused if weighting becomes a political exercise . Given the pros and cons, the authors state that the construction and use of composite indicators is much more like mathematical or computer modelling than a universal science in that it does ultimately rely on the judgement of the researcher or analyst who constructs the tool.

Nardo and Saisana write “As a result, the model of the system will reflect not only (some of) the characteristics of the real system but also the choices made” (Nardo & Saisana, 2005)

4.5.3 Index Technique – Z score normalization / Standardization

The z score normalization, or standardisation was utilized in the study by Haghshenas and Vaziri (2012). Essentially, this technique utilizes statistical concepts, the z score equation, on the indicator data to normalize all data to a common scale. Nardo et al describe this technique as follows: “… converts indicators to a common scale with a mean of zero and standard deviation of one. Indicators with extreme values thus have a greater effect on the composite indicator. This might be desirable if the intention is to reward exceptional behaviour. That is, if an extremely good result on a few indicators is thought to be better than a lot of average scores.” (Nardo M. , et al., 2005)

4.5.4 Index Technique -Rescaling and Distance to Reference

Two other techniques to be discussed are the rescaling and distance to reference techniques. The manual by Nardo et al (2005) was also used to inform the thesis project’s use of these techniques.

The first technique, re-scaling, normalises the set of values for a particular indicator to have an identical range of values (Nardo M. , et al., 2005). The authors suggest that this transformation can be used to set up an identical range (for example 0-1). However, Nardo et al (2005) describe that extreme values, leverage data points, and outliers can have distorting events on the transformed datasets – meaning higher performing values will be closer to maximum, and lower performing values will be closer to the minimum. The authors caution that this could stretch data across a greater distance than it was prior to normalization for some indicators, which may have implications for the composite indicator.

Distance to a reference measures the position of a given indicator relative to a reference point – as described by Nardo et al there are a few types of reference points that can be used:

- Temporal targets – goals to be reached by a set point in time (i.e. a CO_2 reduction goal) are used as a reference point or target.
- External benchmarks – using a system (i.e. a country that other countries will be compared to) as a benchmark that is used as a reference point or target.
- Average target – the average value for the data being analysed is used as reference point or target.
- Group Leader target – the highest performing value in the data set or group is used as a reference point or target.

Adapted from (Nardo M. , et al., 2005)

The "utility" technique was used by Jeon (2007) and Jeon et al. (2009) for evaluating different plan alternatives in Metropolitan Atlanta. This technique, as applied in the study, essentially compares all indicators to the highest performing indicator in the same category, and normalizes them between 0 and 1 (inclusive). This technique is similar to the one described by Nardo et al (2005) namely rescaling and 'distance to reference'. In particular it could be described as applying these techniques with the group leader target.

The application of these techniques is discussed in the methodology chapter.

4.5.5 Weighting Discussion

Conducting an exercise to determine weighting will be out of scope for this thesis, however techniques will still be discussed in brief to both inform the placement of this thesis among the literature but to also allow future studies to take off where it leaves off. According to Sinha and Labi (2007) in MCDM type process, weighting is a critical issue and allocating weights of each criteria relative to one another is a key step to determining the overall decision making framework (Sinha & Labi, 2007). Nardo et al (2005) also stress the importance of rigorous weighting approaches and provide a summary of techniques and their uses in the development of composite indicators (Nardo M. , et al., 2005). Similar to the Jeon studies and Haghshenas & Vaziri (2012), applying a weighting technique to this study is outside of the scope of the project. There are also interesting questions posed by applying a weighting tool to the project – if multiple systems are used, should local stakeholders from each system's locale be consulted in the development of the weighting or overall should experts be sought for weighting?

A variety of techniques have been reviewed in texts and studies including Jeon (2007), Sinha and Labi (2007), and Nardo et al (2005). Nardo et al provide a more general overview of weighting techniques, while the others provide transport specific approaches. These techniques include equal weighting, direct weighting, regression-based observer derived weighting, the Delphi technique, and the analytic hierarchical process (AHP). The equal weighting approach utilized in this study, as well as Jeon's study is critiqued for its simplicity by Sinha and Labi as it does not incorporate preferences that may exist between some criteria.

In recent years, transport and sustainable transport studies have aimed to enrich MCDM and weighting techniques in numerous ways. For example, diverse stakeholder opinions can be utilized in an AHP process, such as the methods applied by Castillo and Pitfield (2010) through surveys and questionnaires. Weighting was developed in their study from transport planners and academics for both weighting criteria for indicator selection as well as objectives for sustainable transport. It is possible these techniques can be used to reach a wider stakeholder audience when broader participation is desired.

4.5.6 Survey of Indicator Sets

To date, many research and reporting efforts have compiled technical reports and research articles that contain sustainable transport indicators. In particular, Dobranskyte-Niskota & Pregl (2007), Haghshenas & Vaziri (2012), Jeon, Amekudzi, & Guensler (2009), Litman & Burwell (2006), Litman (2013), and the Sustainable Transportation Indicators Subcommittee (2009). Jeon and Amekudzi (2005) also reviewed 16 initiatives and developed a long list of transport measures of sustainability along with their review of sustainability frameworks and definitions.

This section of the thesis shares the major summary tables or indicator sets used by the authors. There is no consensus on where certain indicators should fit into sustainability frameworks – for example Jeon, Amekdudzi, & Guensler (2009) include travel time as a user cost in the economics category whereas Dobranskyte-Niskota & Pregl (2007) include it as a factor of accessibility.

These discrepancies speak to the complexity of sustainability but also how sustainability analysis is open to interpretation. As a result, it has been a challenging endeavor to build upon these established frameworks, as well as research into key elements of transport, such as accessibility, with consistency. In the following sections these indicators will be explored in greater detail and an explanation of how to apply them to transit research will be provided.

Table 4-2 Litman 2013 Sustainability Indicators

Sustainability Goals	Objectives	Performance Indicators
I. Economic		
Economic productivity	Transport system efficiency. Transport system integration. Maximize accessibility. Efficient pricing and incentives.	▫ Per capita GDP and income. ▫ Portion of budgets devoted to transport. ▫ Per capita congestion delay. ▫ Efficient pricing (road, parking, insurance, fuel, etc.). ▫ Efficient prioritization of facilities (roads and parking).
Economic development	Economic and business development	▫ Access to education and employment opportunities. ▫ Support for local industries.
Energy efficiency	Minimize energy costs, particularly petroleum imports.	▫ Per capita transport energy consumption ▫ Per capita use of imported fuels.
Affordability	All residents can afford access to basic (essential) services and activities.	▫ Availability and quality of affordable modes (walking, cycling, ridesharing and public transport). ▫ Portion of low-income households that spend more than 20% of budgets on transport.
Efficient transport operations	Efficient operations and asset management maximizes cost efficiency.	▫ Performance audit results. ▫ Service delivery unit costs compared with peers. ▫ Service quality.

Sustainability Goals	Objectives	Performance Indicators
II. Social		
Equity / fairness	Transport system accommodates all users, including those with disabilities, low incomes, and other constraints.	▫ Transport system diversity. ▫ Portion of destinations accessible by people with disabilities and low incomes.
Safety, security and health	Minimize risk of crashes and assaults, and support physical fitness.	▫ Per capita traffic casualty (injury and death) rates. ▫ Traveler crime and assault rates. ▫ Human exposure to harmful pollutants. ▫ Portion of travel by walking and cycling.
Community development	Help create inclusive and attractive communities. Support community cohesion.	▫ Land use mix. ▫ Walkability and bikability ▫ Quality of road and street environments.
Cultural heritage preservation	Respect and protect cultural heritage. Support cultural activities.	▫ Preservation of cultural resources and traditions. ▫ Responsiveness to traditional communities.
III. Environmental		
Climate protection	Reduce global warming emissions Mitigate climate change impacts	▫ Per capita emissions of global air pollutants (CO_2, CFCs, CH_4, etc.).
Prevent air pollution	Reduce air pollution emissions Reduce exposure to harmful pollutants.	▫ Per capita emissions of local air pollutants (PM, VOCs, NOx, CO, etc.). ▫ Air quality standards and management plans.

Sustainability Goals	Objectives	Performance Indicators
Prevent noise pollution	Minimize traffic noise exposure	▫ Traffic noise levels
Protect water quality and minimize hydrological damages	Minimize water pollution. Minimize impervious surface area.	▫ Per capita fuel consumption. ▫ Management of used oil, leaks and storm water. ▫ Per capita impervious surface area.
Open space and biodiversity protection	Minimize transport facility land use. Encourage more compact development. Preserve high quality habitat.	▫ Per capita land devoted to transport facilities. ▫ Support for smart growth development. ▫ Policies to protect high value farmlands and habitat.
IV. Good Governance and Planning		
Integrated, comprehensive and inclusive planning	Planning process efficiency. Integrated and comprehensive analysis. Strong citizen engagement. Lease-cost planning (the most overall beneficial policies and projects are implemented).	▫ Clearly defined goals, objectives and indicators. ▫ Availability of planning information and documents. ▫ Portion of population engaged in planning decisions. ▫ Range of objectives, impacts and options considered

(Litman, 2013, p. 82)

Table 4-3 Dobranskyte-Niskota et al 2007 Sustainability Indicators

DIMENSION	THEME	RELATED INDICATORS
Economic	Transport Demand and Intensity	1.Volume of transport relative to GDP (tonne-km; passenger-km)
		2. Road transport (passenger and freight; tonne-km and passenger -km)
		3. Railway transport (passenger and freight; tonne-km and passenger-km)
		4. Maritime transport for goods and passengers (tonne-km and passenger-km)
		5. Inland waterway transport (passenger and freight; tonne-km and passenger-km)
		6. Air transport (passenger and freight; tonne-km and passenger-km)
		7. Intermodal transport (tonne-km and passenger-km)
	Transport Costs and Prices	8. Total per capita transport expenditures (vehicle parking, roads and transit services)
		9. Motor vehicle fuel prices and taxes (for gasoline and gas/diesel)
		10. Direct user cost by mode (passenger transport)
		11. External costs of transport activities (congestion, emission costs, safety costs) by transport mode (freight and passenger)
		12. Internalization of costs (implementation of economic policy tools with a direct link with the marginal external costs of the use of different transport modes)
		13. Subsidies to transport
		14. Taxation of vehicles and vehicle use
		15. % of GDP contributed by transport
		16. Investment in transport infrastructure (per capita by mode/ as share of GDP)
	Infrastructure	17. Road quality - paved roads, fair/ good condition
		18. Total length of roads in km by mode
		19. Density of infrastructure (km-km^2)
Social	Accessibility and Mobility	20. Average passenger journey time
		21. Average passenger journey length per mode
		22. Quality of transport for disadvantaged people (disabled, low incomes, children)
		23. Personal mobility (daily or annual person-miles and
		24. Volume of passengers
	Risk and Safety	25. Persons killed in traffic accidents (number of fatalities -1000 vehicle km; per million inhabitants)
		26. Traffic accidents involving personal injury (number of injuries – 1000 vehicle km; per million inhabitants)

DIMENSION	THEME	RELATED INDICATORS
Social	Health	27. Population exposed to and annoyed by traffic noise, by noise category and by mode associated with health and other effects
		28. Cases of chronic respiratory diseases, cancer, headaches. Respiratory restricted activity days and premature deaths due to motor vehicle pollution
	Affordability	29. Private car ownership
		30. Affordability (portion of households income devoted to transport)
Environmental	Transport Emissions	32. NOx emissions (per capita)
		33. VOCs emissions (per capita)
		34. PM10 and PM2.5 emissions (per capita)
		35. SOx emissions (per capita)
		36. O3 concentration (per capita)
		37. CO_2 emissions (per capita)
		38. N20 emissions (per capita)
	Energy Efficiency	40. Energy consumption by transport mode (tonne-oil equivalent per vehicle km)
		41. Fuel consumption (vehicles-km by mode)
	Impacts on Environmenta l Resources	42. Habitat and ecosystem disruption
		43. Land take by transport infrastructure mode
	Environmental Risks and	44. Polluting accidents (land, air, water)
		45. Hazardous materials transported by mode
	Renewables	46. Use of renewable energy sources (numbers of alternative-fuelled vehicles) - use of biofuels
Technical and operational	Occupancy of Transportation	47. Occupancy rate of passenger vehicles
		48. Load factors for freight transport (LDV, HDV)
	Technology Status	49. Average age of vehicle fleet
		50. Size of vehicle fleet (vehicle/ 1 mln. inhabitants)
		51. Proportion of vehicle fleet meeting certain air emission
Institutional	Measures to Improve Transport Sustainability	52. R&D expenditure on "eco vehicles" and clean transport Fuels
		53. Total expenditure on pollution prevention and
		54. Measures taken to improve public transport
	Institutional Development	55. Uptake of strategic environmental assessment in the transport sector

Adapted from (Dobranskyte-Niskota, Perujo, & Pregl, 2007)

Table 4-4 Haghshenas & Vaziri 2012 Sustainability Indicators

Indicator	Description	Unit
	Environmental	
Energy	Transport energy use per capita	Mj
Land Use	land consumption for transportation infrastructure per capita	M
Emissions	Emissions of local air pollutants (CO, VOC, NOx) per capita	kg
	Economic	
Cost for Government	Local government expenditure on transport per GDP	%
Direct transportation cost per user	Average daily cost over GDP per capita	%
Indirect Transportation Cost	Average time spent in traffic	Minutes
	Social	
Safety	Fatalities per capita	Persons
Accessibility	Sum of transportation systems for every citizen passenger km per area	M
Variety	Sum of transportation option vehicles per capita divided per maximum of that option vehicle per capita in all cities	-

(Haghshenas & Vaziri, 2012)

Table 4-5 Bongardt et al 2011 Sustainability Indicators

Economic	Social	Environmental
• Minimum taxation on fuel • Transport investment by mode • PKM/TKM per unit GDP	• Road fatalities • Modal share of PT/NMT • Share of costs as function of household expenditure	• Land consumption • Greenhouse gases, • Population impacted by local pollutants

(Bongardt, Schmid, Cornie, & Litman, 2011)

Table 4-6 Jeon et al 2009 Sustainability Indicators

Sustainability dimension	**Goals and objectives**	**Performance measures**
Transportation system effectiveness	A1. Improve mobility	A11. Freeway/arterial congestion
	A2. Improve system performance	A21. Total vehicle-miles traveled
		A22. Freight ton-miles
		A23. Transit passenger miles traveled
		A24. Public transit share
Environmental sustainability	B1. Minimize greenhouse effect	B11. CO_2 emissions
		B12. Ozone emissions
	B2. Minimize air pollution	B21. VOC emissions
		B22. CO emissions
		B23. NO_X emissions
	B3. Minimize noise pollution	B31. Traffic noise level
	B4. Minimize resource use	B41. Fuel consumption

		B42. Land consumption
Economic sustainability	C1. Maximize economic efficiency	C11. User welfare changes
		C12. Total time spent in traffic
	C2. Maximize affordability	C21. Point-to-point travel cost
	C3. Promote economic development	C31. Improved accessibility
		C32. Increased employment
		C33. Land consumed by retail/service
Social sustainability	D1. Maximize equity	D11. Equity of welfare changes
		D12. Equity of exposure to emissions
		D13. Equity of exposure to noise
	D2. Improve public health	D21. Exposure to emissions
		D22. Exposure to noise
	D3. Increase safety and security	D31. Accidents per VMT
		D32. Crash disabilities
		D33. Crash fatalities
	D4. Increase accessibility	D41. Access to activity centers
		D42. Access to major services
		D43. Access to open space

(Jeon, Amekudzi, & Guensler, Evaluating Plan Alternatives for Transportation System Sustainability: Atlanta Metropolitan Region, 2009)

4.5.7 Indicator Selection Criteria

From the indicators outlined previously, a selection has been made for a short list to be considered for further analysis for this thesis based upon the best practices for indicator selection from the literature review. The overall criteria utilized for this selection process were adapted from Litman (2013) as well as Castillo and Pitfield (2010).

4.5.8 Public Transit Goals and Objectives

Based on the literature review of sustainable transportation and public transit, a synthetic set of goals and objectives has been assembled to aid in public transit sustainability analysis. This table draws upon the frameworks, indicator sets, and sustainability discussion of numerous authors included in chapters 2,3 and 4 and is intended as a heuristic to guide the selection of public transit indicators for this research project.

Each sustainability goal has been framed as an objective which could be expressed mathematically in future research as part of an objective equation minimization or maximization process. In the next section, each goal and objective will be discussed in-depth in terms of past studies and methods for handling data or measuring the indicator. Further considerations for each goal and objective are included in chapters 5 and 6. It should be noted that this table contains goals as specified for this research and sustainability analysis should be a living analysis, meaning revision and adaptation to new knowledge and emergent issues should be common.

Table 4-7 Sustainability Goals and Objectives for Mass Transit

	Goal	Objective	Linked to
Environment	Decrease passenger Energy Use	Minimize energy consumed/pkm	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri), (Litman)
	Decrease passenger contribution to climate Change	Minimize ghg emissions /pkm	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri), (Bongardt, Schmid, Cornie, & Litman), (Jeon, Amekudzi, & Guensler), (Litman)
	Decrease Pollution - Land, air, water	Minimize pollutants or emissions/pkm	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri), (Jeon, Amekudzi, & Guensler) , (Litman)
	Limit Ecological Disturbance	Minimize disruption by right of way and system construction	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri), (Bongardt, Schmid, Cornie, & Litman), (Jeon, Amekudzi, & Guensler), (Litman)
Economy	Reduce user cost	Reduce Travel Time	(Dobranskyte-Niskota, Perujo, & Pregl – as social), (Haghshenas & Vaziri), (Jeon, Amekudzi, & Guensler), (Litman)
		Reduce direct monetary costs	(Dobranskyte-Niskota, Perujo, & Pregl), (Litman)

	Goal	Objective	Linked to
	Increase system economic efficiency	Reduce operating cost per unit of travel	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri)
		Reduce capital cost	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri)
	Improve System independence	Maximize recovery or reduce required subsidy.	(Dobranskyte-Niskota, Perujo, & Pregl)
	Increase demand relative to GDP	Maximize passenger km travelled relative to GDP	(Dobranskyte-Niskota, Perujo, & Pregl), (Bongardt, Schmid, Cornie, & Litman)
Social	Improve affordability	Minimize cost of transit as portion of user or household income	(Dobranskyte-Niskota, Perujo, & Pregl), (Jeon, Amekudzi, & Guensler), (Litman)
	Increase accessibility	Maximize accessibility across multiple dimensions (user, system)	(Dobranskyte-Niskota, Perujo, & Pregl), (Haghshenas & Vaziri), (Bongardt, Schmid, Cornie, & Litman), (Jeon, Amekudzi, & Guensler), (Litman)
	Limit health impacts	Minimize exposure to and illness/death fro, human health impacting emissions	(Dobranskyte-Niskota, Perujo, & Pregl), (Bongardt, Schmid, Cornie, & Litman), (Jeon, Amekudzi, & Guensler),

	Goal	Objective	Linked to
	Limit safety impacts	Minimize injury and death from system operation	(Dobranskyte-Niskota, Perujo, & Pregl), (Bongardt, Schmid, Cornie, & Litman), (Jeon, Amekudzi, & Guensler), (Litman)
System Effectiveness	Improve operations and capacity utilization	Maximize reliability and capacity utilization	(Dobranskyte-Niskota, Perujo, & Pregl), (Litman)
	System Usage	Maximize the ridership of transit	(Bongardt, Schmid, Cornie, & Litman), (Jeon, Amekudzi, & Guensler), (Litman)

These goals and objectives can be utilized in analysing proposals or existing systems. As outlined in the table, efforts have been made to select a diversity of indicators utilizing elements from past studies as well indicators from these reviews of indicator sets that are reflective of the general state of research in sustainable transportation. The following sections outline techniques from the literature, where appropriate, or state common methods to measure and utilize these indicators.

4.6 **Environmental Indicators**

4.6.1 Energy

Sustainable transportation systems should reduce their consumption of energy (Banister, Unsustainable Transport: City transport in the new century, 2005) Inasmuch, when comparing transit systems on sustainability performance, energy consumed per unit of mobility produced has been selected as an indicator. Potter's (2003) review of energy and emission studies for automobiles finds that the majority of emission and energy comes from usage, he suggests that this may hold true for urban transit as well. Other studies have shown that there are large amounts of energy embedded in right of way construction (Rahman, 2009). This thesis is concerned largely with system operation, and not the life cycle – however future studies may be able to take into account Rahman's findings on a larger scale.

Using energy as an indicator either requires a reliable data source on energy consumption, or the ability to estimate energy consumption from transit parameters.

An early study of energy consumption by Fels in 1974 considered the entire life cycle of transportation – that is, the energy embedded in the manufacture of the vehicle, the guide way, and the operation. This study focussed on auto, bus, and rapid rail transit systems, along with personal rapid transit and estimates for dial a ride and motorcycle transport. This study used reported values from agencies for major modes, as well as analytical estimates where necessary and reported all findings in terms of energy required per vehicle mile.

Other studies, such as Jong & Chang (2005) reviewed mathematical models to estimate the energy consumption of electric railways. These studies were to aid in planning and developed new insights and useful tools. In the Jong and Chang study the impact of the system and vehicle/rolling stock was not explored in depth. It can be generalized that system energy consumption is largely a function of rolling stock and fuel, as well as the route the vehicle travels. Energy requirements of the system are based on a variety of factors that have been collected from a number of sources, including:

- **Vehicle Factors**: vehicle design, mass, and traction system contribute to the energy requirements for propulsion. Vuchic (2007) indicates that LRT vehicles in general may offer higher space per unity of power than heavy rail vehicles, based on a survey of common rail vehicles.
- **Vehicle velocity:** the operating speed of the vehicle along corridor segments impacts the energy required. Velocity can be calculated using an average or based on travel profiles between stops.
- **Efficiency**: input/output for the vehicle's propulsion system.
- **Fuel source**: different types of fuel used for propulsion (diesel, electricity, compressed natural gas, etc. ...) provide different amounts of energy
- **Occupancy/payload**: the expected occupancy of the vehicle along the corridor changes vehicle mass. Occupancy can be an average for the corridor or be based upon occupancy between stops.
- **Frequency**: the number of vehicles over a given time that services the corridor.
- **System layout:** location of stops, number of stops, dwell time at stops
- **Right of way factors:** grade, traction, geometric conditions
- **Energy system factors**: losses in transmission, type of transmission system used

(Vuchic V. R., Urban Transit Systems and Technology, 2007) (Rahman, 2009) (Jong & Chang, 2005) (Potter, 2003) (Puchalsky, 2005)

While past studies have made efforts to estimate energy consumption along a rail line or for a bus route, many agencies report energy consumption for propulsion. For example, in the United States of America, all agencies that receive federal transit funding report their consumption of energy to the Federal Transit Administration for the National Transit Database in terms of either in Kilowatt Hours or gallons of diesel (Federal Transit Administration, 2013). Other studies, such as Puchalsky (2005) use NTD as a starting point for energy analysis.

In his review of public and private transport in Toronto, Kennedy utilized historical data to capture energy consumption as well (Kennedy C. A., 2002). This analysis includes a review of past studies that highlights life cycle energy costs of vehicles, as well as infrastructure. Estimates are utilized where historic data is not available.

These studies provide key insights that can inform how to estimate or accurately measure the energy use indicator for public transit for this thesis research. These are summarized in Table 4-8.

Table 4-8 Summary of Energy Indicator Studies

Authors	Techniques and Considerations
(Rahman, 2009)	• Compared LRT and BRT indirect and direct energy costs based on vehicle, infrastructure, operations • Utilized life cycle estimations
(Fels, 1974)	• Compared a variety of modes based on vehicle, infrastructure, and operations • Utilized historical data and analytical calculations, including life cycle calculations
(Jong & Chang, 2005)	• Developed and reviewed analytical models for energy consumption
(Kennedy C. A., 2002)	• Compared public and private transport on a variety of sustainability parameters • Energy was compared using historic data for operations and estimations when data was not available • Energy measured in MJ/seat km, MJ/ vehicle km or MJpkm

While life cycle assessment of infrastructure and vehicles is outside of the scope of this research, it is included in many influential studies and its importance is worth mention. This study's energy indicator will be MJ/pkm.

4.6.2 Emissions – local and global pollutants

Emissions are a nearly universal indicator for sustainable mobility. All frameworks reviewed for this thesis included elements of greenhouse gas and local emissions, such as PM, NOx, SOx, and other pollutants. This thesis considers emissions in terms of their raw value, as a pollutant to the environment, as well as an impact on human health. This perspective captures past discussions that consider damage to environmental capital and intergenerational equality as well as ensuring systems limit overall negative impact on environment independent of human considerations.

Past studies can be applied to include and analyze emissions indicators in this thesis. Puchalsky (2005) put forward a study focussed entirely on the emissions factor. His efforts utilized a useful methodology based on the National Transit Database and emission factors. By using energy consumption levels from the Light Rail mode as well as passenger mile travelled values, Puchalsky was able to calculate average energy per unit of passenger travel. These values were then multiplied by emission factors to determine mass of pollutant for volatile organic compounds, CO, and NOx. The best case and average LRT were compared to hybrid, CNG, and normal bus systems based on previous studies. Upstream processes (energy costs in production of fuel) were not counted in either BRT or LRT models, only energy generation at plant, line loses, and LRV vehicle uses were included in the LRT case, and bus fuel delivery and bus emissions in the BRT case.

The overall findings were that BRT produced greater emissions than LRT despite improvements in diesel combustion technology (Puchalsky, 2005). As this thesis seeks to work with large data sets in the comparison of mass transit systems, this methodology can be adapted – including the use of the Leonardo Academy factors. For studies where high level energy data and grid data are known, this approach is useful.

Puchalsky's equation for calculating emissions from eGrid values as well as NTD emissions and PKM values has been adapted with minor modifications for general public transit vehicles as displayed below:

$$E_{pj,i} = \frac{f_{j,s}c_{s,j,i}}{pkm_j}$$

(adapted from Puchalsky, 2005)

- Where E_p is the quantity of emissions of pollutant i for system j;
- Pollutant i represents either greenhouse gases or local pollutants
- and f is the quantity of energy or fuel consumed by system j in state s;
- and c represents the emission factor for pollutant i in state s

This general form equation can be utilized in a variety of cases and will be applied in this thesis. Puchalsky also suggests two additional equations for BRT mode emissions which can be utilized for the specific BRT case.

A generalized approach to considering emissions in public transit planning is to also consider the emission reductions along with the emissions created by public transit travel. Hughes and Zhu (2011) from the institute for Transport and Development Policy provide a case study of the Guangzhou BRT system that utilizes this BRT case expression:

$$\sum M\ (R)(S_M)(D_{M)}(E_M) = I_{mode\ shift}$$

Where

- I = Cumulative yearly emissions avoided from other modes in tonnes of emissions
- M = Mode used before BRT implementation
- R = Yearly cumulative ridership for bus routes included in BRT corridor
- S = Modal shift for mode (M)
- D = Average travel distance for mode (M)
- E = Emissions factor for mode (M)

(Hughes & Zhu, 2011)

While this case is intended for BRT, it is general and can be used for any mode as long as the equation's parameters are known. Specific BRT equations for impacts on vehicle speed on emissions are also provided within the report. These equations can be applied for all emissions for which emissions factors are known, including climate change impacting emissions.

Climate change gases can be considered using the same approach as outlined previously for emissions, only with a special class of emissions for CO_2 and other greenhouse gases that can be measured as CO2E or individually. CO2 Emissions are strongly linked to energy consumption for modes that utilize fossil fuel energy sources (Banister, Cities, Mobility, and Climate Change, 2008). This has two interesting implications:

- Public transit presents an opportunity to lower emissions of GHgs per trip (more passengers per vehicle, different fuel sources and fuel efficiencies), as well as for the overall system (diverting trips to public modes, improving efficiencies of other modes), thus reducing a transport system's contribution to global climate change (Hughes & Zhu, 2011) (Schiller, Bruun, & Kenworthy, 2010).
- However, many public transit systems still use fossil fuels directly (diesel buses) or indirectly (electricity purchased for electric light rail vehicles)

These implications must be considered when considering system impacts on climate change.

In general, emissions can be considered as a function of:

- **Vehicle technology and operations**: how the vehicle utilizes the fuel in the case of internal combustion.
- **Energy Source**: either the fuel or the power plant/transmission system providing energy to the transit system.

As they fall into the field of power engineering and vehicle design, further discussion of these factors are outside of the scope of this thesis, but are worth mentioning. Emission studies are summarized in Table 4-9.

Table 4-9 Transit Emission Studies

Authors	Summary
(Puchalsky, 2005)	• Compared LRT to BRT on emissions • LRT achieves better performance across factors considered • Utilized e-gird approach
(Vincent & Walsh, 2003)	• Compared BRT, LRT, and Metro style systems based on emissions • Found an advantage for BRT technology • Utilized the "eGrid approach" for calculating emissions of electric rail systems

The metric used for this indicator is the mass of pollutant emitted per trip, passenger km travelled (or other distance), or vehicle km travelled (or other distance). All these metrics have been used in the literature. For the purpose of comparing different mass transit systems, utilizing a passenger km travelled basis is deemed most appropriate as it compares the system's actual performance per unit of transit work created for a passenger's journey. While a rigorous framework would consider the impact of pollutants on land, air, and water, past studies have looked largely at quantifying emissions. Given scoping constraints of this research, it will similarly analyze end of pipe or power plant emissions of transit systems as mass/pkm.

4.6.3 Noise

Noise has been explored in the past as a management and economics issue as an externality of transport as well as a physical concept to be measured. Gillen provides an in depth description of noise issues as both a physical phenomenon (acoustic levels of noise) as well as behavioural to noise dependent on the time of day. Under this treatment, noise occurring from transport can be measured in terms of decibels occurring from the transport project and be compared to acceptable values. The second category, the behavioural response, can be assessed based on choice models that aim to understand how noise impacts an individual's selection of housing location (Gillen, 2003). Alternative techniques, such as the use of expert opinion may also be used to understand the behavioural response to noise.

In the USA, large transit projects normally require noise assessments as part of their environmental impact assessments (Hanson, Towers, & Meister, 2006). As a result there are methodologies to understand the noise impacts of transit projects that are well developed and very nuanced. Hanson et al (2006) developed an in depth evaluation protocol for the Federal Transit Administration that provides insight into basic noise concepts, noise impact criteria, including an overview of noise sensitive land use, and considerations for applying noise criteria. The procedures included in the manual provide in-depth evaluation criteria for how to evaluate specific transit projects as well as useful calculations and standards . As this study is focussed on comparison of multiple systems, such an approach is not practical due to the enormous data collection and calculation efforts that would be required.

4.6.4 Habitat and Ecological Impacts Indicator

Dhingra et al (2003) discuss the environmental impact assessment (EIA) approach to ecological impact based on area impacted by the transportation project. While this indicator is often included in sustainability frameworks, the authors have suggested that these impacts are not always recognized because systems are built on a project by project basis and ecological impacts can occur over time. The methodology provided by the authors is to combine qualitative and quantitative methods to measure impacts of the system. For the quantitative measurement two principles are provided:

- Damage to an area is proportional to the length of the transport option to be provided
- Damage is severe if the ecology is high quality

  (Dhingra et al, 2003)

The authors provide two weighted sum equations: $\sum Wm_jL_j$ amd $\sum Wn_jL_j$ where W is a weight, L is the system length running through a segment of natural or man-made ecosystem, Wm represents the importance or weight of man-made ecosystem j, and Wn represents the importance or weight of man-made natural ecosystems j. These equations can be used to calculate the impact of different alternatives, or in theory existing systems if known weights exist. Reference tables are provided by the authors. This technique is recommended for calculating ecological disturbance, however it is overly reliant on reference weights for ecologies so these reference weights need to be applied consistently if this technique is to be used. Systems seek to minimize their impact score.

An alternative technique is to measure the land footprint of the system. This technique simply measures the overall right of way area of the system as a proxy indicator for system impact on ecology. However, this technique lacks the rigour of weighting different types of ecology. The trade-off is that it deals in area as opposed to just length – perhaps a hybrid indicator can be utilized in future studies that combines the weighted impact described by Dhingra, Rao, and Tom with an area methodology.

4.7 **Economic Indicators**

4.7.1 Operating cost Efficiency

Frameworks in the literature, particularly summaries by Littman (2013) and Dobranskyte-Niskota, Perujo, & Pregl, (2007) emphasize cost effectiveness as a key sustainable transportation indicator. Efficiency can be expressed as the cost of operating a vehicle, the cost of a trip, or the cost of a km of service.

4.7.2 User Costs

Time and monetary costs are counted in multiple frameworks as key indicators assessing economic sustainability. In Litman’s 2013 review of indicators, cost efficiency is listed as an economic indicator of sustainable transportation and a lower value is considered ideal. Performance comparison between other systems in particular is suggested. In the comparison of alternatives or systems, the system that minimizes user costs is said to have the best cost efficiency.

Other studies, such as Jeon (2007), and Kane's (2010) study on sustainable transport indicators in cape town also included average journey time. In the case of Jeon, travel time was specified by an analytical model, while it can also be studied through historical data as well.

4.7.3 Recovery and Subsidy

Past discussions highlighted how systems should cover the costs of their transportation services in order for transport to be sustainable. While these discussions covered toll roads and private auto, the discussion can also be extended to transit systems. This indicator analyses how much of the costs of a transit system are able to be recovered by user costs. As provided in the indicator sets, this is measured as a percentage point.

4.7.4 Transit Activity and Economic Activity

This indicator is outlined by Dobranskyte-Niskota, Perujo, & Pregl (2007) as a given transportation modes activity relative to GDP.

4.8 **Social Indicators**

As previously discussed, social impacts of transportation are difficult to quantify and analyze. As a result, performance measures for social impacts differ in scale, severity, and intensity depending on the frame of analysis (Sinha & Labi, 2007).

4.8.1 Affordability

In Litman's 2013 review of sustainable indicators, affordability is listed as both an economic and a social indicator. As direct user costs are counted as an economic indicator in this study, affordability, as interpreted in the literature review will be counted as a social indicator. Affordability is expressed as the portion of income utilized for transport expenditures (Litman, 2013) (Dobranskyte-Niskota, Perujo, & Pregl, 2007). While indicator sets often express this as portion of household income, other denominations could be utilized as well – such as individual income.

4.8.2 Human health impacts

A number of studies measure human health impacts – two to be discussed are Jeon (2007) and Kennedy (2003). The first is health impact by emissions, which mirrors the discussion put forward in chapter 3.These indicators consider both physical injury due to collision or impact as well as emission related illness or health impacts.

In addition, future frameworks or research should consider the relative health benefits of transit systems based on their integration with active transport (i.e. walking or cycling). This integration would show higher levels of activity and would reflect improved fitness as a result of transit use. However, these issues may be difficult to quantify.

4.8.3 Accessibility

Accessibility is commonly noted as a key indicator in the literature for social aspects of transportation. However, Silva and Pinho argue there is no universal definition in the literature for this commonly used concept (Silva & Pinho, 2006). Silva and Pinho suggest accessibility is difficult to define because it considers many ideas - distribution of destinations, magnitude, quality and character of activities, performance of system, characteristics of individuals, and times for which they participate in activities.

Geurs & Wee (2004) provide an overview of accessibility and its role in evaluation of transportation. This paper provides an overview of different perspectives on accessibility as well as how to utilize different measures to inform evaluation (Geurs & Wee, 2004). Within the paper, accessibility is defined as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)." (Geurs & Wee, 2004).

For this study, a review was conducted of public transit indicators related to accessibility. A key study was conducted by Al Mamun and Lownes in 2011 on composite public transit accessibility indices. In this study the authors propose accessibility is based on three components – trip coverage (transit links travellers to their destinations), spatial coverage (transit is closer to their home/destination), and temporal coverage (transit is available at the time of travel) (Al Mamun & Lownes, 2011). Under this framework, accessibility can be considered as the system's ability to provide a connective service in close proximity to the user's home/destination in reasonable time. The authors conducted a thorough review of existing accessibility measures and have developed a new measure grounded in GIS techniques and accessibility theory. Three techniques are used in the study:

- Local Index of Transit Availability (LITA) – which considers capacity, frequency, and coverage.
- Transit Capacity and Quality of Service Manual
- Time-of-Day Tool

Accessibility is also treated in Hagshenas & Vaziri (2012) where it is considered on a city level. Their study of sustainability focusses on developing a composite accessibility measure that combines the accessibility gains of all systems within a city via the following equation:

$$Transportation\ Accessibility = \sum_{i=1}^{j} \frac{\frac{pkm_i}{Capita}}{\text{urban area}}$$

- Where pkm_j is the passenger km travelled for system i;
- urban area and population are derived from the city being studied
- i represents the set of systems or modes available in the city

This indicator is useful as it relies on high level data (pkm, population, area) which are readily available compared to the data needed for some of the GIS and other accessibility based indicators that are reviewed in this literature. However, it also lacks nuance and rigour as a result.

Cumulative opportunity measures are one of the simplest activity based accessibility measures measuring either the number of opportunities reachable within a travel time, distance or cost, or the average travel time, distance, and cost to reach a fixed number of opportunities (Silva & Pinho, 2006).

In Kane's South African study, an accessibility indicator was put forward that analyzed accessibility in terms of access by elderly, disadvantaged, and children (Kane, 2010). Within the literature is a push to also consider transportation's ability to provide service to a diverse set of user's needs under the banner of 'accessibility'. This includes a focus on indicators that measure whether a system provides access for users with special physical needs (Litman, 2013). Indicators can be derived from the percentage of facilities or vehicles that are equipped to handle special user's needs.

4.9 **Effectiveness Indicators**

Many works cover the topic of transit system performance and the evaluation of public transportation efficiency and effectiveness. Vuchic's 2007 text Urban Transit Systems and Technology covers the foundational topics in measuring and assessing the performance of a given transit system –these concepts are considered essential for developing a comprehensive transit evaluation framework. Vuchic outlines transport as the movement of a number of objects, over a distance, during a period of time. Based on these three elements 6 basic performance attributes are defined:

- Speed: space/time and Slowness: time/space
- Density: objects/space and Spacing: space/objects
- Frequency: objects/time and Headway: time/objects

(Vuchic V. R., Urban Transit Systems and Technology, 2007)

These basic concepts are useful foundations for understanding more advanced transit concepts and are included here for discussion and completeness' sake.

4.9.1 Reliability and Capacity Utilization

The first two indicators are reliability and capacity utilization, which are common in transit analysis. Reliability can be measured in numerous ways, but a common definition is the percentage of vehicles in revenue service that adhere to their scheduled arrival time – Vuchic discusses the value of improved reliability on transit service having numerous benefits across the entire system (Vuchic V. R., 2005). These benefits can include fewer delays, more effective passenger loading, more economic vehicle operations, better allocation of fleet, improved service for passengers, and other benefits which can improve transit's overall performance leading to reduced economic costs (cross cutting benefits) and improved ridership.

Along with the basic attributes of transit performance Vuchic outlined that were previously discussed, Vuchic also discussed a concept called "Transportation Work" denoted with 'w' described as the 'number of objects multiplied by the distance over which they are carried' (Vuchic V. R., 2007). This parameter can be useful for measuring the effectiveness of a system and can be measured using a number of units such as passenger km travelled or vehicle km travelled.

In terms of measuring the utilized capacity, work provides a useful concept. If a transit system is imagined as having an overall theoretical capacity that is linked to work and is defined as the total work that a system can do as defined by the number of passenger kms travelled a system can produce for a given period of time, as measured by the kms travelled by every unit of seat and standing capacity of every vehicle based on the definitions created by Vuchic, then the effectiveness measure proposed is based on the actual amount of passenger kms travelled on that system divided by the work produced is proposed. This indicator uses work utilized to measure the amount of capacity utilized.

4.9.2 System Usage

System usage factors are suggested in frameworks such as Jeon, Amekudzi, & Guensler (2009)and Dobranskyte-Niskota, Perujo, & Pregl (2007). Dobranskyte-Niskota, Perujo, & Pregl suggest using pkm as a measure, however these frameworks are for looking at systems holistically as opposed to just transit so these measures are not suggested to be applied directly in this study. If studying the overall sustainability of a transport system (composed of active modes, auto, transit, etc. . .) these indicators may be more suitable. However, in this study, multiple transit systems are being compared so pkm can be used as a standardizing factor for comparing factors (such as GHg emissions) between systems. In this case an additional measure of system usage should be adopted. Raw ridership numbers cannot be utilized as smaller cities will be shown to be less sustainable in comparison to larger cities in the case that larger cities may have larger trip or pkm due to population. In This case, pkm or trips per capita should be used, or systems should be compared by population levels. Mode share is an alternative.

4.10 Conclusion

Chapter 4 reviewed the literature on sustainable transport analysis, using MCDM tools for research and decision making in the transport sustainability field, past studies of transportation system sustainability, tools for using composite indicators/indices, and indicator frameworks. These concepts are presented to demonstrate the wide breadth of the subjects and introduce enough depth for the construction of the research project’s framework and research methodology in chapter 5, where a new methodology that builds on past research is presented.

The general finding from this literature review is that MCDM type tools are useful for sustainable transportation analysis as they enable the researcher or analyst to consider problems in terms of multiple perspectives and develop an analysis that takes these perspectives into account, as opposed to other decision making tools which may only allow one or two issues to be considered. When using sustainability frameworks, such as the triple bottom line, this is ideal. Composite indicators allow a MCDM type process to be communicated simply by returning multiple accounts or categories of analysis into a single index or indicator for comparison – in the case of the Jeon studies and Haghshenas and Vaziri (2012) a composite indicator of transportation system sustainability. From this review a basic set of objectives and goals were formulated in the vein of past indicator frameworks and studies to be used for public transit studies. Specific information from past studies and texts on assessing each goal and objective has been provided for the development of the framework – this information will be relied upon in chapters 5 and 6.

Chapter 5: Mass Transit Composite Sustainability Assessment Methodology

5.1 Chapter Overview

This chapter outlines the methodology developed for sustainable transportation analysis and how it has been set up for this study. First, the chapter presents an overview of the methodology and how it can be used in different contexts to study sustainable transportation or assist in analysis and decision making through the use of indicators and indices. This overview outlines the key steps of the methodology including data selection and collection (methodology part 1), data analysis and treatment in order to run a sustainability analysis (methodology part 2), and selection of techniques to create a composite index (methodology part 3).

Next, the chapter details the specific indicators that have been selected for studying mass transit systems based on current practice and understanding of sustainable transportation within the literature. As outlined in chapter 4, there are numerous indicators that can be used for sustainable transportation assessment – this chapter shares the ones adapted for this methodology along with how they can be applied. Continuing, the chapter shares how the methodology is applied including information on data collection through three alternative techniques for calculating composite indices – the z score approach, the reference value approach, and the rescaling approach. Next, chapter 5 continues by comparing these three approaches for calculating composite sustainability indices, and contrasts this methodology to other sustainability analysis methodologies from the literature. Finally, the chapter concludes with limitations of this methodology and how it could be expanded or improved in future studies to provide a more comprehensive understanding of the sustainability of public transportation.

5.2 Overview of Methodology

The methodology used in this study has been named the "Public Transport Sustainable Mobility Analysis Project" or PTSMAP and has been developed based on the goals and framing of this study outlined within chapter 1, along with key learning, best practices, and current thinking on sustainable mobility and mass transit systems that have been identified in the literature review. The development of this methodology and the demonstration of its implementation explores research question 1.

The overall framework is based on principles discussed in the literature review. In the literature, sustainability framework, principles, and the science behind them have been discussed at length along with their application to the analysis of transportation systems. This research's contribution is in synthesizing relevant aspects of different frameworks and tools in order to provide a framework for the analysis of mass transit. This methodology represents the synthesis of these concepts, along with the selection of relevant indicators in order to effectively study the research questions posed by this research – how can the contributions of mass transit to sustainability be measured, and how do different mass transit modes contribute to sustainable mobility? This framework has been developed to address both questions: 1) providing an analytical tool to analyze and research transit sustainability and 2) use current data to explore the different sustainability characteristics of transit systems and modes. In essence, the goal of this framework is to develop a conceptual platform that can use a variety of data sources, either from models or collected data, along with evolving understanding of sustainability to inform both planning and research of mass transit systems. Figure 5-1 shares a graphical outline of the methodology:

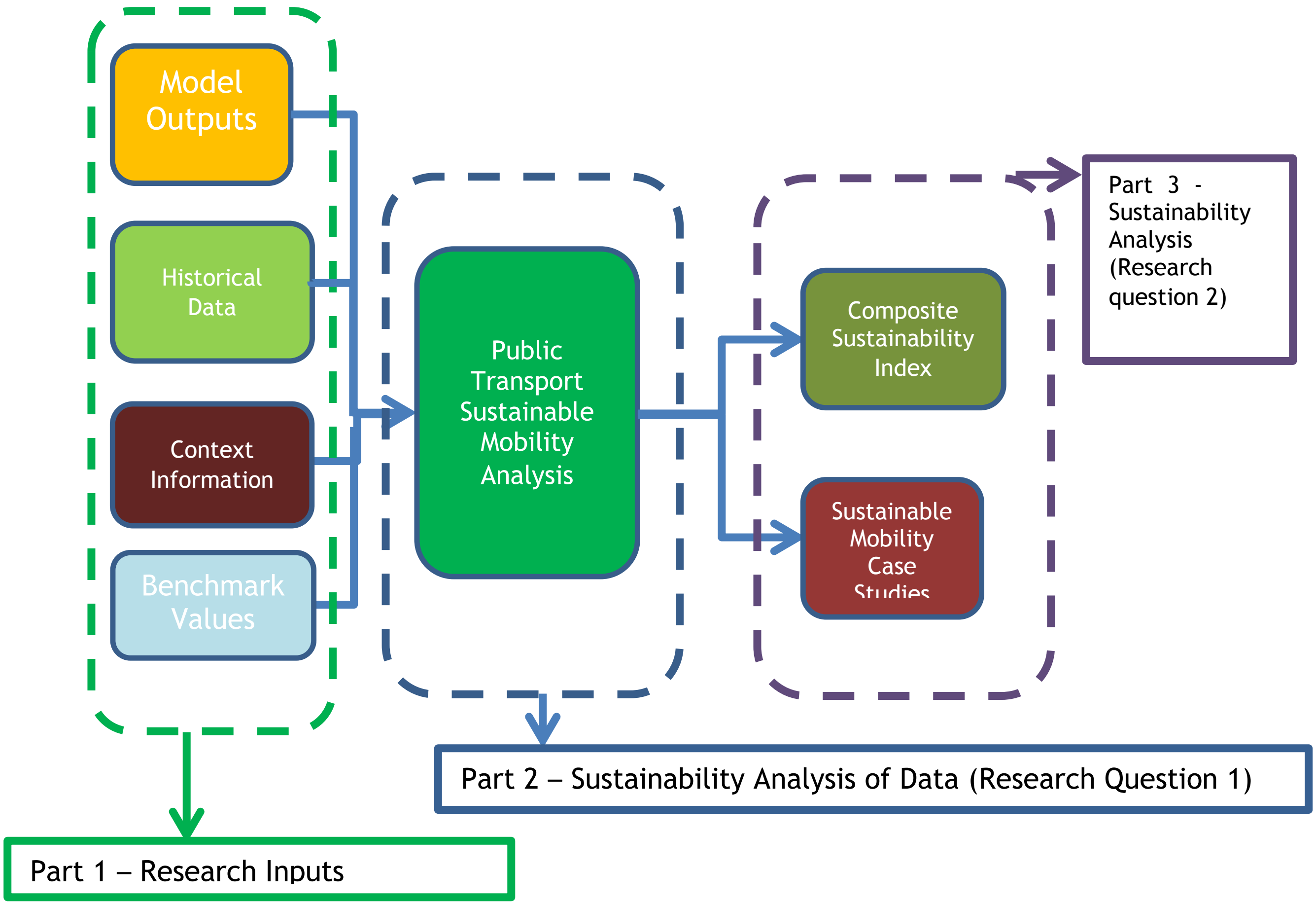


Figure 5-1 Public Transport Sustainable Mobility Analysis Project Framework

The foundation of the PTSMAP framework is an "Impacts Based Framework", as described in the literature review, which includes an explicit focus on the analysis of a mass transit system's impacts on different dimensions of sustainability within the system, the city it serves, the broader geographic context, and global climate. This framework is focussed on first collecting and sorting data based on its type and use for the analysis (**part 1**), and then treating, expanding, and utilizing the data for calculating indices for individual sustainability categories based on inputs and outputs of transit provision (**part 2**), and finally generating a composite sustainability index and case studies to inform understanding of mass transit and sustainable mobility (**part 3**).

The framework can be generally applied in four scenarios:

- **System Comparison 1**: application of the PTSMAP framework for comparison of transit systems in order to determine the relative contributions of each system towards sustainable mobility. This comparison is determined through the calculation of composite sustainability indices.
- **System Comparison 2:** application of the PTSMAP framework for comparison of transit systems in order to determine their contributions to sustainable mobility based on a set of absolute benchmark values for each factor that are based on policy, research, or other criteria.
- **Decision Making 1:** application of the PTSMAP framework for decision making purposes. This framework can be applied beyond research for aiding decision makers in selecting which mass transit system development can produce the greatest contributions to sustainable mobility.
- **Decision Making 2:** application of the PTSMAP framework for decision making purposes. In this scenario the framework is applied to determine which system provides the best performance towards a set of pre-determined benchmark values that are based on policy, research, or other criteria.

For this thesis project, this methodology is utilized in two scenarios based on thesis goals and available data:

1. The analysis of multiple mass transit systems (multiple modes, geographic contexts) for research question 2 based on historic data. (**System comparison 1)**
2. The analysis of potential mass transit systems on a specific corridor or area for system expansion to determine which alternative offers the greatest sustainable mobility benefits. (**Decision Making 1)**

In both scenarios, the different systems being analyzed are characterized as discrete entities with comparable traits for which data is collected and analyzed in order to not only draw comparisons, but also develop understanding on transit and sustainability based on the broader context in which transit is provided. In this analysis sustainability is measured comparatively based on relative system performance on a set factors. This framework could be used to compare systems to set benchmarks on factors that are set as sustainability targets; however that is outside the scope of this research and could be conducted by agencies, governments, transportation professionals, or as future research. With the provided indicator set and methodology, this framework could be expanded with other indicators and data to be used in other scenarios and research projects as well.

The methodology described in this chapter is called the default methodology, which essentially follows scenario 1 and 2 – which is for all intents and purposes identical until the analysis stage where for scenario 1 the purpose is developing novel understanding of transit systems and sustainable mobility, whereas 2 is focussed on making a choice for a transit alternative.

Referring to the classification of MCA tools in chapter 4 taken from Vreeker and Nijkamp (2005), this tool can be classified as follows:

- **Discrete or Continuous? – *Discrete* –** the tool is intended to analyse a fixed set of transit systems although future research could improve it to incorporate linear programming to be involved in design and development.
- **Quantitative, Qualitative or Mixed? – *Quantitative*–** the tool mainly uses quantitative data and only uses qualitative data to contextualize data (i.e. historical information to explain why some systems perform better or why some system alternatives may perform a certain way, which are followed up with empirical studies)
- **Prices or Priorities? – *Priorities*–** the tool is focused on analysing transport contributions and impacts to sustainability through a sustainability lens and is not focussed on monetizing these impacts or pricing them using market structures.
- **Linear or Functions?** – ***Linear*** –the tool uses a weighted sum process to calculate a composite sustainability index although future tools could include

analytical hierarchical processes to integrate decision maker behaviour, or decision maker utility or value functions.

Referring back to Janssen and Munda as cited in Vreeker and Nijkamp (2005) this process would be referred to as a value approach to MCA. Subsequent sections further outline the logic and functioning of the PTSMAP methodology and its integration of MCA and MCDM concepts through its three part framework.

5.2.1 Part 1 – Research Inputs

Part 1 of the framework is concerned with the selection of data for use in the PTSMAP framework. The data that is collected is based on sustainability categories and factors which are used in this study – these requirements and their identification are outlined in section 5.3.

All data used in this framework is labeled as a research input. Research inputs refer to a variety of information sources which can be used to analyze planned or implemented mass transit systems.

In this framework they have been broken down into four categories. Model outputs represents data acquired through analytical modelling which is typically conducted through software, such as EMME. These outputs would be used when the framework is utilized to compare alternatives during planning, or research is being conducted on sustainability on potential improvements to a system or potential new systems, as an example. Alternatively, model outputs can be used to supplement historical data for analyzing existing systems where historical data is either incomplete or cannot be collected.

The second category, historical data, refers to historical or operational quantitative data collected from transit systems. This data is utilized to compare existing systems to better understand how mass transit modes, technologies, and systems configurations, as well as urban factors such as density and economic considerations all impact transit's ability to yield sustainable mobility outcomes. This data can be obtained through transit agencies, such as Calgary Transit or Translink, large open databases, such as the National Transit Database, public transit associations, such as

American Public Transit Association's (APTA) fact book, government agencies, universities, past research, or non-profit organizations.

Context information in this framework refers to information about the transit system, or the city, region or broader geographic area it operates in, which informs the broader understanding of sustainable mobility that is used to inform analysis. Definitions of sustainability in the literature and regional or municipal plans that are subjective are examples of contextual information that inform the development of the composite sustainability index. A second role of qualitative information is in the development of sustainability case studies. After a CSI has been developed, to further the research and enable a deeper understanding of sustainable mobility, qualitative data can be included to provide more in-depth context for the CSI value developed in the quantitative portion of the methodology which is the bulk of this chapter. For analysis, a blend of all types of data can be used. Within this research, the focus has been placed on this quantitative data through the development of indices and factors for measuring sustainability.

Finally, for specific analysis exercises only, benchmark values reflect specific objectives, goals, or targets for sustainability factors which are loaded into the framework. Benchmark values are only used in decision making applications of the framework when comparing how different mass transit systems perform compared to an absolute set of values as determined by policy, research, or other processes. For this research, these values are discussed, but not applied directly.

The data collection step of this framework follows these steps:

1. Outline data requirements for the study based on framework application/scenario
2. Sort data by indicator/factor and by system/mode being compared

The collection and treatment of data is further outlined in this chapter. In chapter 6 actual data is treated in the analysis.

5.2.2 *Part 2- Sustainability Analysis of Data*

Part 2 of the methodology is concerned with utilizing the data gathered and treated in part 1 to run an analysis based on sustainability principles. The process for part 2 follows data collection with the comparison of separate transit systems or modes by sorting data based on a variety of indicators which have been sorted into categories which represent this research's working definition of sustainable mobility. In the analysis stage, the framework considers system inputs, such as operational costs or quantity of energy for vehicle movement, as well as system outputs, such as number of people moved or emissions of greenhouse gases, which are part of providing mass transit services.

This process is illustrated in Figure 5-2, where inputs, and system impacts of different transportation systems separated by mode are considered. Although this process could also be used for different transit plan alternatives that are of similar mode, this research is focussed on exploring the sustainability performance of transit systems by mode to determine if there is an inherent difference in the performance achieved by these modes.

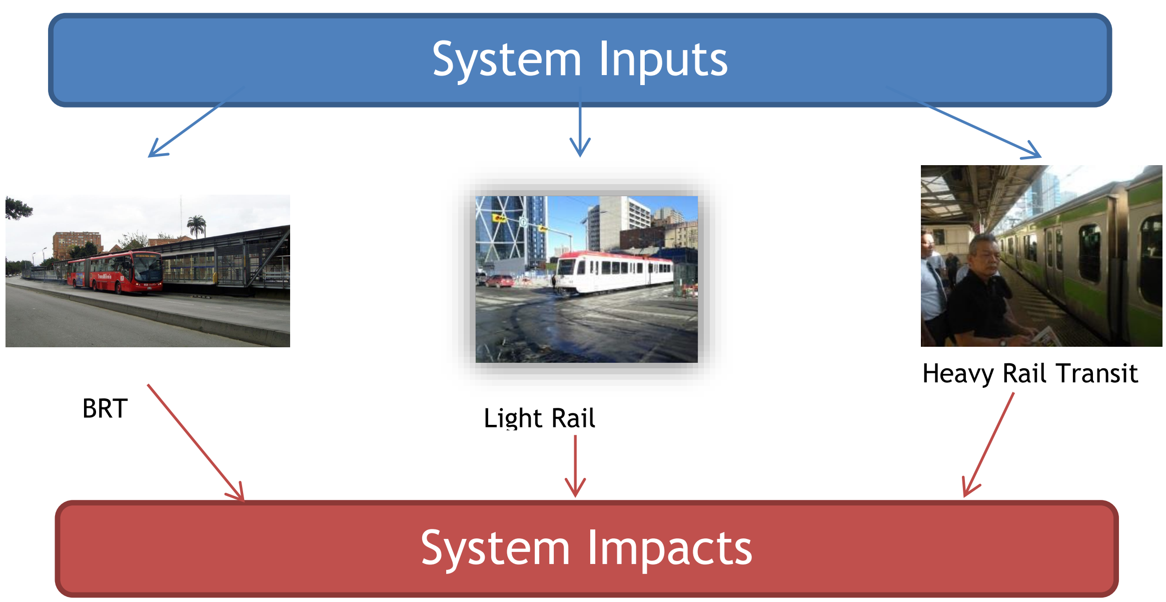


Figure 5-2 Modal or Alternative Comparison

The analysis is structured based on multi criteria analysis, as outlined within the literature, and utilized in various sustainability analysis studies, notably Kennedy in 2002, Jeon in 2007, Jeon et al in 2009, and Haghshenas and Vaziri in 2012. For this analysis a structure has been developed based on treating the data from part 1 of the framework in order to develop a composite sustainability index as described in Jeon et al, Jeon, and Haghshenas and Vaziri, which is based on adding weighted sustainability categories together in part 3 of the framework. These four works provide both a theoretical foundational structure as well as mathematical underpinning for which this methodology is based upon.

In essence, this analysis methodology outlines the appropriate categories for mass transit sustainability analysis to enable data sorting, treatment and expansion, normalization, and ultimately the calculation of indices for each sustainability category used in the study. Four categories have been selected for this study based on work by Jeon in 2007 and Jeon et al (2010), as well as foundational concepts in urban transit and sustainability analysis.

Three categories are typical in sustainability discourse and research: environmental, economic, and social. The fourth is system effectiveness, which was utilized in the ground breaking research by Jeon in 2007, as well as Jeon et al in 2010 to analyze auto network transport in the Atlanta region. Effectiveness of public transit and broader transportation systems has been studied at length; however, its inclusion in comprehensive sustainability analysis is recently emergent in the literature. Each category contains both costs and benefits – or positive and negative impacts. This approach determines how well a system balances the four categories – the better a system performs in each category, the more balanced it is towards contributing to sustainable mobility. This relationship is outlined in Figure 5-3.

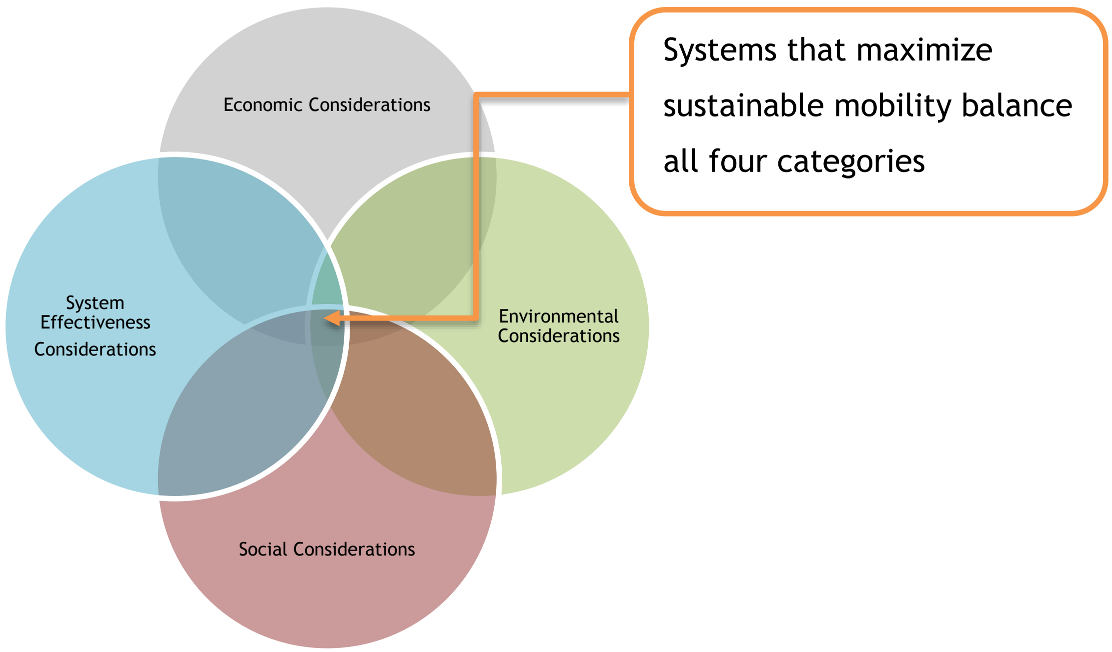


Figure 5-3 Visualisation of Sustainability Assessment

Adapted from (Jeon, Incorporating Sustainability Into Transportation Planning and Decision Making: Definitions, Performance Meaures, and Evaluation (Dissertation), 2007) (Litman, Well Measured - Developing Indicators for Sustainable and Livable Transport Planning, 2013)

The economic category represents the economic costs of the systems to society and the user, as well as the economic contributions of public transit to society. The environmental category represents how the system interacts with the natural environment, including ecosystems locally and globally. The social category represents how the system promotes human welfare or limits it through the provision of transit service. Finally, the system effectiveness category represents how effectively transit service is provided.

This assessment methodology utilizes data from part 1 in order to develop indices for each category based on factors that represent indicators of sustainability within the particular category. A weighted sum equation is used to calculate an index for each category based on factors that fit into that category. The structure of analysis used is as follows:

- **Indices -** represent the weighted sum of all factors within a category (i.e. environmental index) or the sum of all categorical indices (CSI)
- **Factors** – numerical representations of the indicators of benefits, costs, or impacts of mass transit within a certain category. Factors are grouped together under categories. (i.e. climate change emissions is an environmental factor)
- **Indicators** – set descriptors for a performance measure of sustainable mobility factors. (i.e. CO_2 and CH_4 emissions are indicators for climate change emissions)

The calculation of indices follows equation 5-1:

$$I = \sum_{i=1}^{j} w_i f_i$$

Equation 5-1 Category Index Equation

- Where I represents an index for a sustainability category;
- w represents the weighting of factor i.
- and f represents factor i of category I which has been transformed through an index methodology. Positive impacts are added, negative impacts are subtracted or signed negative – these are discussed in section 5.3-5.7;

Each index can be useful for comparing mass transit systems based on that particular category, for example, environmental terms, in addition to being used for calculating the composite sustainability index.

Each category has one index which may be composed of any number of factors based on the objectives and scope of the analysis and available data. Indicator selection and factors are outlined in section 5.3.

To summarize, the following process is followed for the part 2 methodology:

1. **Treatment and expansion:** select the relevant data from part 1 for factor j and apply relevant treatment and expansion as required by the data. Based on the data set being used, standardize the data for cross comparison. For example, when comparing GHg emissions, the standardization process is dividing by annual system wide pkm travelled.
2. **Performance Analysis:** analyze the performance of each system under each indicator based on the raw data.
3. **Normalization:** use techniques that allow all the data to be combined into a composite indicator.

5.2.3 Part 3 – Calculating the CSI

Part 3 of the methodology is concerned with the development of a composite sustainability index as well as sustainability case studies to inform sustainability research.

In order to calculate a CSI, a weighted sum equation is utilized as adapted from the work of Jeon et al (2009) and Haghshenas and Vaziri (2012)– both of whom applied a similar methodology to use a composite sustainability index to study sustainable mobility in different contexts as outlined in chapter 4. Similar to both methods, this methodology utilizes weighting of overall factors for each sustainability category index, - in this case *environmental, social, economic, and effectiveness* – as well as weighting for each factor that represents each index (this is described in part 2). Equation 5-2 represents the calculation of a composite sustainability index for this methodology including the four categories and their factors.

Equation 5-2 Composite Sustainability Equation

$$CSI_q = w_e \sum_{i=1}^{L} w_i E_{i,q} + w_s \sum_{i=1}^{M} w_i S_{i,q} + w_n \sum_{i=1}^{N} w_i N_{i,q} + w_y \sum_{i=1}^{O} w_i Y_{i,q}$$

Adapted from (Jeon, 2007) (Haghshenas & Vaziri, 2012).

Where:

- CSI represents the composite sustainability index for a system q
- w represents either weighting value for the environmental, social, economic, or system effectiveness category, or factor i within that category;
- e represents environmental factors;
- y represents system factor;
- s represents social factor;
- n represents economic factor;
- Ei represents normalized environmental factors i-L used in this study;
- Si represents normalized social factors i-M used in this study;
- Ni represents normalized economic factors i-N used in this study;
- and Yi represents normalized system effectiveness factors i-O used in this study

In this formulation all weighting factors for category indices as well as factors must sum to 1, that is:

$$w_e + w_s + w_n + w_y = 1$$

And

$$\sum_{i=1}^{j} w_i = 1$$

Once the CSI values are generated, an analysis can be conducted based on sustainability principles and urban factors of the individual systems. These are discussed in the analysis section.

5.3 Discussion and Selection of Indicators and Factors

For this study, a collection of factors from the literature review have been selected for inclusion based on their relevance to the research questions as well as criteria that establish quality indicators from the literature review on decision making.

5.4 Environmental Category

The environmental category has four factor sets: energy use, pollution, land use and consumption, and greenhouse gas emissions.

5.4.1 Energy Factors

This factor is concerned with the amount of energy required to move mass transit vehicles and ultimately passengers as part of mass transit service provision. Energy consumed should be calculated on a per passenger distance travelled basis for overall sustainability analysis. For this study, energy required to develop and construct transit systems has not been considered; however this could be included in future revisions through the inclusion of life cycle methodologies.

Many agencies and researchers have stressed the need for decreased energy consumption for transport to tend towards greater sustainability, as is reflected in the literature review.

As discussed previously in the literature review, in terms of environmental efficiency, sustainable systems aim to provide high capacity mobility with lower energy expenditure than private modes so all energy indicators should be normalized on a per passenger km travelled basis.

Two indicators for the energy factor are worth including in this section – for systems that use electrical vehicles, such as typical LRT systems or metro systems, an energy indicator is proposed. For vehicles that use fuel, typically diesel, such as a diesel fueled BRT system, a fuel indicator is listed for use, which may be converted into an energy value either based on a known average energy content of the fuel, or an approximation based on fuel standards. All energy indicators are considered negative impacts.

Table 5-1 Energy Indicators

Indicators	Metric	Data Requirements and notes
▪ **Quantity of energy consumed**	▪ MJ consumed /pkm	▪ Energy supply data (electric powered systems), source of electricity and quantity either by route/line or for full system
▪ **Quantity of fuel consumed**	▪ Litres consumed/p km	▪ Fuel supply data - quantity and type either by route/line or for full system ▪ Fuel supply ultimately will be converted into energy

5.4.2 Pollution - emissions and noise

The pollution factor set is this framework's facility for considering pollutants that have a localized impact including NOX, VOC, PM, SOx, and noise. The factor utilizes two indicators for the analysis of environmental sustainability. The first is concerned with pollutants produced in the operation of transit to provide mobility. Localized pollution has many impacts on the environment, as outlined within the literature review chapters, including the formation of photochemical smog.

In the case of this factor set, common pollutants associated with the particular set of mass transit systems being researched may be chosen or in the case of utilizing this framework as a decision support system, based on the technologies and modes involved in the decision being considered, the appropriate pollutants may be selected using knowledge about the choices being considered. Any number of indicators could be used in this case. Indicators should be added using environmental research on regulation or impacts of technology being reached or analyzed in order to determine which indicators are relevant. The second indicator, noise, similarly may use historic data or model data; however, the use of noise, as discussed in the literature review, is difficult in high level studies due to the quality of data and complexity of analysis required. For this study, pollution released during the construction of the transit systems has not been considered, however this could be included in future revisions through the inclusion of life cycle methodologies. All pollution indicators are considered negative impacts.

Table 5-2 Pollution Indicators

Indicators	Metric	Data Requirements
▪ **Mass of pollutant (i.e. NOx, VOC, CO, SO2, PM, Hg) emitted into soil, air, and water**	▪ kg/pkm	▪ For research of existing systems: ○ Emission inventories ○ If inventories are unavailable, these items can be derived by looking at energy data including fuel source and quantity burned. ○ Emissions can be done systemically or for individual components or routes. ▪ Models, technological details, forecasts may be used as a data source for these indicators
▪ **Noise**	▪ Decibels on corridor/pkm	▪ Models ▪ Available noise data.

5.4.3 Land consumption and ecosystem degradation

Land consumption measures the amount of physical environment consumed to provide the transit service. Typically, this land is consumed in the development of guide way (roads, tracks) and station or stop area. Land consumption is a proxy indicator for variety of environmental impacts –ecosystem disruption, run off due to impermeable surface, and use of urban environment or limited land resources to provide mobility rather than environmental services. Land consumption should be normalized as a percent of total urban area. All land use indicators are considered negative impacts.

An alternative measure is the Dhingra, Rao, and Tom (2003) measure that utilizes right of way length and ecological impact weights to measure ecological impact of the system. This indicator can be used in studies but requires consistency in the application of weights.

Table 5-3 Land Use Indicator

Indicators	Metric	Data Requirements
▪ **Land area consumed by transit facilities**	▪ $metres^2$	▪ Design details and system plans, ▪ The length of a particular system, as well as its width. ▪ Station footprints ▪ Area can be done systemically or for individual components or routes.
▪ **Ecological impacts of right of way**	▪ meters	▪ Design length of system ▪ Types of areas impacted by system and their relative weights

5.4.4 Global Climate Change- Green House Gas Emissions

GHg emissions represent the system's impact on global climate change via the greenhouse effect The GHgs included in this methodology are: CO2, CH4, and N20. They are added together and included as a single indicator of CO2 equivalents. For this study, greenhouse gases released during the construction of the transit systems have not been considered, however this could be included in future revisions through the inclusion of life cycle methodologies which have been used in studies by other authors such as Rahman (2009). All GHg indicators are considered negative impacts.

Table 5-4 Global Climate Change Indicator

Indicators	Metric	Data Requirements
▪ **Mass of CO2 Equivalents of CO_2, CH_4, N_2O, emitted into the atmosphere**	▪ Mass of CO_2 equivalents/ pkm	▪ GHg inventory ○ If inventories are unavailable, these items can be derived by looking at energy data including fuel source and quantity burned which can then be multiplied by emissions factors. ▪ GHg can be done systemically or for individual components or routes.

5.5 Economic Category

The economic category includes factor sets related to user costs, system costs, and system contributions to economic growth and development.

5.5.1 Total Operating Costs

Operating costs represent the amount of monetary resources required to maintain and operate the mass transit system under various time frames. These indicators reflect the monetary inputs required to operate a given mass transit system for a fixed time frame. For this framework, the time frame has been set to one year – consistent to the literature. Operating costs are composed of a number of issues including staffing, maintenance of vehicles and right of way (depending on type of service provided and operating agreements) (Vuchic V. R., Urban Transit Operations, Planning, and Economics, 2005). For the intents of this research, operating costs are seen as a factor that should be minimized, as is consistent with economic objectives within the literature review, and will be treated at a macroscopic level without entering into the many mescoscopic and microscopic specific costs that compose operating costs at a specific agency. All costs are negative inputs.

Table 5-5 Operating Cost Factors

Indicators	Metric	Data Requirements
▪ **Annual operating cost**	▪ $/pkm	▪ Annual operating costs ▪ Total expenditure on transit ▪ Total expenditure on transportation

5.5.2 Capital *Costs*

Capital costs represent the overall system costs for construction of the infrastructure. These costs can be used for a variety of analysis – such as cost/km or by simply looking at the overall cost across multiple systems. As this research is aimed at understanding how systems achieve sustainable mobility, it is important to consider the overall costs. Capital costs are a difficult point of comparison between systems, however, due to a number of reasons. One key reason is that systems are often assembled over long periods of time – complete sets of data for the overall cost for a system are difficult to come by and are not in the same economic terms requiring significant data mining to adjust for changes in costs of goods and labour over time. Further, when comparing capital costs between systems, it is important to build in different economic contexts into the analysis. For example, costs of construction, planning, and development are not endogenous to transit systems themselves.

When developing this methodology to compare the sustainability of different transportation systems or routes planned for development within a single geographic context, the complications of including capital cost in analysis decreases significantly. For example, when comparing between different alignments of a hypothetical LRT route within a city, the complications of data analysis are not as significant depending on data availability. Costs should not include stations or stops and should be concerned with the provision of transit right of way or guide way required for vehicle movement. All costs are negative inputs.

Table 5-6 Capital Cost Factors

Indicators	Metric	Data Requirements
▪ **System wide capital costs**	▪ $	▪ Raw or adjusted cost data per right of way length across the system ▪ Station costs are not included, cost should only include right of way.
▪ **Individual route capital costs**	▪ $	▪ Raw or adjusted cost data for individual routes ▪ Station costs are not included, cost should only include right of way.

5.5.3 Recovery and Subsidy

This factor set looks at the total recovery of costs due to fares. This represents the short term economic sustainability of the system. It is argued in the literature that for truly sustainable mobility individuals need to pay the full cost of their travel. It is also argued that as transit approaches 100% recovery, it will reach economic sustainability. In both instances, as these indicators are percentages they require no normalization for comparison. Both of these indicators are seen as positive.

Table 5-7 Recovery and Subsidy Factors

Indicators	Metric	Data Requirements
▪ **% of costs recovered**	▪ %	▪ Passenger revenue/total operating cost.
▪ **% of costs subsidized**	▪ %	▪ Subsidization scheme data

5.5.4 Transit Usage Relative to Economic Activity

This factor measures the utilization of the transit systems relative to economic activity in the communities served by the transit system.

Table 5-8 Transit Usage Relative To Economic Activity

Indicators	Metric	Data Requirements
▪ PKM per unit GDP (passenger km travelled)	▪ PKM/$	▪ Total PKM (daily, annual) ▪ GDP of study area

5.5.5 User Costs

User costs represent the economic costs incurred on the traveller accessing the system. In this study, costs are measured in time and money. Financial cost is represented as the average price each user pays per trip, and time cost is represented by the average time spent on transit by each user. All costs are negative inputs.

Table 5-9 User Cost Factors

Indicators	Metric	Data Requirements
▪ Average Financial Cost	▪ $/trip or pkm	▪ Overall system revenue and ridership
▪ Average Time Cost	▪ Minutes/ trip	▪ Average vehicle speed, total passenger revenue hours

5.6 Social Category

Social factors in this research include accessibility, health, and safety.

5.6.1 Accessibility

Accessibility represents the ability of people to use the transit system to reach destinations or activities they desire. There is a debate in the literature about how to best measure accessibility and as a result there are many formulations, measures, and approaches applied to the term. For this research, the goal of accessibility is to understand how the transit performs for local populations based on their needs to travel. Two issues are selected – one looks at accessibility through a network view, the second considers it through a user view.

The first accessibility indicator is selected due to the high level nature of this framework. While GIS tools can be utilized to perform specific accessibility studies on specific transit networks, this study is designed to compare multiple networks so an agile indicator is ideal. The accessibility network index has been used in CSI studies to assess how overall transport systems provide mobility (Haghshenas & Vaziri, 2012). Based on its past utility, it is used first in lieu of rigorous methods which require specific in-depth data and analytic techniques outside of the scope of this study. According to Haghshenas & Vaziri (2012) accessibility can be calculated as passenger km per capita/urban area. This factor essentially represents the average amount of passenger kms traveled by each person per unit of urban area – a higher value indicating a more accessible system. This indicator is a proxy for how well the system serves the population of a given urban area based on the amount of work the system creates per person per unity of area in the city.

In situations where a more comprehensive data set or analytical toolset is available, the cumulative opportunity accessibility index is suggested as a second accessibility indicator which would be used instead of, not in conjunction with, the accessibility network index.

Transit access is the third indicator in the accessibility set. It utilizes the percent of urban area within a planning distance (example, 400 m radius catchment area) of mass transit stations. In situations where cumulative opportunity is not possible, this indicator can provide an estimate of accessibility by indicating transit coverage.

Average user trip length is the next indicator which is a companion to indicators which focus on system accessibility. This indicator is concerned with the amount of distance each individual must travel on the system to get to their destinations. This indicator is a representation of how accessible the system is to the user’s day to day needs and a lower average trip length is desirable.

The next indicator covers accessibility based on the end user by analyzing affordability. Average cost is divided by income per capita to represent, in general, how much access costs are in proportion to an individual’s income within the area served by the transit system. Additionally, mean or median income could be utilized for this indicator. Access costs are included in this portion of the thesis. In this methodology, the tool has been set up on a per pkm, per trip, and per capita basis, to analyze either units of mobility or units of trips for use with large data sets and comparison between systems. However, if a representation of the central income of users or households, rather than per capita income, should be used for assessing affordability and access to transit it is suggested that careful analysis between mean and median income be undertaken in order to determine which is more appropriate. This is based on a discussion by Orzechowski & Seipeilli (2003) on the high positive skewness of incomes in the USA and the mean value's sensitivities to extreme observations. The report, published by the US Census Bureau, advocates for the use of median values instead (Orzechowski & Sepielli, 2003) .

The final indicator is a measure of accessibility for people with special needs related to physical disability. A common trend in the literature is to highlight the need to consider all potential users needs when planning, designing, and implementing transit systems. The metric selected for this framework is the percent of vehicles and stations that are considered accessible based on local accessibility standards or legislation.

Accessibility indicators are positive inputs, where larger values are desirable for all indicators except for affordability where a smaller affordability ratio is desirable.

Table 5-10 Accessibility Factors

Indicators	Metric or Unit	Data Requirements
▪ **System Accessibility Index**	▪ Passenger km per capita/urban area	▪ Network length or route length, passenger totals, urban area
▪ **Cumulative Opportunity**	▪ Jobs/Activity centres linked by transit system	▪ GIS data on travel between zones using transit for jobs, activity centres
▪ **Transit Access**	▪ % of urban area within planning distance of transit station	▪ Planning data on stop location, urban area
▪ **Average User Distance**	▪ Distance travelled per trip	▪ Number of trips and total pkm per year
▪ **Affordability**	▪ Fare/ income per capita ▪ Portion of household income devoted to public transport	▪ Fare rates ▪ Household expenditures on transit and transport
▪ **User Accessibility**	▪ % of stations accessible to all users ▪ % of vehicles accessible to all users	▪ Stations equipped with accessibility features ▪ Vehicles equipped with accessibility features

5.6.2 Health

This factor set analyzes the population exposed to pollution and its negative impacts. As discussed in the literature review, emissions due to all forms of motorized transport create health risks. For transit systems that emit localized pollutants, the negative impacts can be captured and quantified.

The first indicator utilizes available data on population living, working, and accessing activity centres surrounding transit lines as well as pollution models to calculate the population exposed to types of pollutants. The second indicator uses city wide data and mathematical models to calculate the disease burden related to the quantity of transit pollutants.

Both health indicators are negative impacts.

As mentioned in Chapter 4, future research could include another health indicator that is based on the extent to which the use of transit promotes positive individual health – such as improved fitness resulting from increased physical activity.

Table 5-11 Health Factors

Indicators	Metric or Unit	Data Requirements
▪ **Population exposed to emissions related to transit.**	▪ People	▪ Data on population surrounding transit lines or power sources ▪ Pollution models
▪ **Disease burden related to transit systems**	▪ Number of deaths	▪ Data on deaths due to diseases that can be attributed to transport pollution

5.6.3 Safety

This factor analyzes the toll on human life of the transit system based on two indicators – fatalities and accidents. These indicators are already based on operations and do not need to be normalized as a result.

Both safety indicators are negative impacts.

Table 5-12 Safety Factors

Indicators	Metric or Unit	Data Requirements
▪ **Persons killed per 1000 VKM, million inhabitants operation**	▪ Fatalities/1000 VKM ▪ Fatalities/Millio n inhabitants	▪ Population ▪ Transit related deaths ▪ Total vkm travelled
▪ **Accidents per 1000 VKM, million inhabitants operation**	▪ Accidents/1000 VKM ▪ Accidents/milli on inhabitants	▪ Transit related accidents

5.7 Effectiveness Category

The effectiveness category contains operating and system usage factor sets, which capture how well the system provides transit service.

5.7.1 Operating and Capacity Factors

This factor set looks at factors that represent how well the system provides effective rapid transit services. The first indicator analyzes capacity utilization of the system as a percentage of available capacity on vehicles. For this study, achieving higher capacity is seen as effective transit utilization. The second indicator considers the percentage of vehicles in the system that are reported on time – the more vehicles on time, the more reliable the system is. As these indicators are a percentage no normalization is required for comparison between systems. Both indicators are positive.

Table 5-13 Operating and Capacity Indicators

Indicators	Metric	Data Requirements
▪ **Average Occupancy rate of passenger vehicles**	▪ %	▪ Data on occupancy and ridership for the system or specific routes ▪ Types of vehicles in fleet, number of seats, operational configuration of vehicles
▪ **Reliability**	▪ % on time	▪ Reliability data

5.7.2 System Usage Factors

The indicator for system usage is annual trips per capita in the urban area served by the transit system. It can also be represented by modesplit. This indicator represents the system's ability to attract riders and generate trips as a proxy indicator for level of service of the transit system. This indicator is a positive input.

Table 5-14 System Usage Factors

Indicators	Metric	Data Requirements
▪ **Annual Trips per Capita**	▪ Number of trips/Population in the city	▪ Data on daily and annual trip totals per system or route
▪ **Modesplit**	▪ % of trips	▪ Mode split data

5.8 Application of Methodology - Normalization and Weighting

Parts 1-3 of the methodology can be applied to assess the comparable contributions to sustainability of transit systems. With the factors and indicators identified along with data requirements, part 1 of the methodology can be followed and data can be collected. Parts 2 and 3 can then be followed to conduct a sustainability analysis; however, in order to complete parts 2 and 3, data must be normalized. In this section of the chapter three techniques used in the literature to develop composite indices –

the z-score, utility techniques, and rescaling – are discussed which are required to conduct the analysis discussed in parts 2 and 3.

Nardo (2005) described normalization as the process of ensuring different variables can be summed up by making them comparable. Different normalization techniques are available and it is important to select one that matches the objectives of the composite index (Nardo & Saisana, OECD/JRC Handbook on constructing composite indicators. Putting theory into practice., 2005). These techniques general involve comparison within a set of factors (i.e. comparing all user fare costs) in order to generate a data set that represents original range of data, but can now be combined with other factors to create a composite indicator. For example, in their raw form, the amount of energy consumed and the mass of emissions released are in different units and are not readily combined to construct an index. However, once normalized they will be unit-less and combined based on weighting.

5.8.1 Technique 1: z-score function

The first methodology for calculating the composite sustainability index has been utilized by Haghshenas & Vaziri (2012) in their calculations of composite sustainability indices for the global comparison of municipalities' transportation systems. This approach utilizes a z -core equation to treat each individual factor for each system being analyzed. In this approach, indices are real numbers – with larger positive indices representing greater contributions to sustainable mobility.

Equation 5-3 is utilized:

$$Z = \frac{x - \mu}{\sigma}$$

Equation 5-3 z-score equation

Where:

- x represents the factor being analysed;
- μ represents the arithmetic mean of that factor for all systems;
- and σ represents the standard deviation of that factor for all systems

For this methodology the following steps are followed:

1. Calculate the standard deviation and mean for all factors considered in the analysis
2. Calculate z-score values for each factor, for each system
3. Set weights for each factor and index
4. **Part 2:** Apply the category index equation for each category to generate categories as described in part 2
5. **Part 3:** Apply the composite sustainability index equation to generate the CSI as described in part 3

5.8.2 Technique 2: Distance to Reference Based Approach

This approach to calculating the CSI was utilized in Jeon (2007) and Jeon et al (2009) for calculating a CSI in the Atlanta metropolitan area. In both approaches, each factor is normalized based on a linear single attribute utility function in order to compare among plan alternatives. Nardo et al (2005) refer to this as a reference value based approach because the data is normalized to a set reference. In the case of Jeon (2007) and Jeon et al (2009) the highest performer is used as a reference value. In this methodology, indices and normalized factors are real numbers between 0 and 1, where the greatest performing system within a single factor receives a score of 1.

For this methodology, a similar approach has been adopted where factors are normalized between systems based on the following process:

- For factors that are positive impacts:

Equation 5-4 Positive Impact Factor Equation

$$\boldsymbol{n_i = \frac{x_i}{Max\,(all\;x)}}$$

Where x is a factor, n is the normalized factor, and i represents a particular system.

- For factors that are negative impacts:

Equation 5-5 Negative Impact Factor Equation

$$\boldsymbol{n_i} = \frac{\boldsymbol{Min\ (all\ x)}}{\boldsymbol{x_i}}$$

For this methodology the following steps are followed:

1. Calculate linear scaled values for each factor
2. Set weights for each factor and index
3. **Part 2:** Apply the category index equation for each category to generate categories as described in part 2
4. **Part 3:** Apply the composite sustainability index equation to generate as CSI as described in part 3

5.8.3 *Technique 3: Re-scaling*

Nardo et al (2005) outlined rescaling as a useful technique to normalize data. This technique is similar to technique 2 in that it is the range and not the standard deviation that normalizes the data (Nardo M. , et al., 2005). It is a general form which has been adapted as follows in Equation 5-6:

Equation 5-6 Re-Scaling Equation

$$n_i = \frac{x_i - \min(all\ x)}{\max(all\ x) - \min(all\ x)}$$

Adapted from Nardo et al 2005 - where n is the normalized factor, x represents the factor in raw form, and i represents the system being analysed. The max and min relate to the leader (max) and laggard (min) for the particular variable. Nardo et al caution that extreme values or outliers may cause the normalized data to be distorted.

For this process the same steps are followed as in technique 2.

5.8.4 Comparison of techniques

These techniques have been used in studies to apply sustainability concepts to the analysis of transportation systems. While both techniques can develop a composite sustainability index, they have different purposes. The utility approach was outlined for use in decision making amongst a set amount of alternatives in Jeon (2007), while the z-score approach was outlined for comparison in Haghshenas & Vaziri (2012). This thesis employs both techniques to demonstrate their application within this methodology.

The z-score technique utilizes statistical concepts and was employed in Haghshenas & Vaziri (2012) to compare multiple cities from a global database on several transportation factors. The results of this study allowed interesting trends, relating sustainability factors to urban factors, such as density, to be identified for a large data set. This technique compares each factor based on its value relative to the average value of the data set.

The utility approach was employed by Jeon (2007) and Jeon et al (2009) for comparing plan alternatives and is reliant on decision making principles. The output of this approach is an index between 0 and 1, which may be clearer when communicated to decision makers and easier to use in conjunction with visualization tools such as the polygon used in Jeon (2007). Jeon analyzed three cases, rather than the expansive data set used in Haghshenas & Vaziri (2012) to demonstrate how to use sustainability in decision making between plan alternatives. This technique ranks system factors based on their utility compared to the best alternative (in the case of a positive factor) or the worst alternative (in the case of a negative factor) and is intended for decision making scenarios – outlining a more sustainable alternative amongst a set of plan alternative modes to better understand how each system compares based on sustainability criteria to make a decision.

5.8.5 Weighting

Weighting for each factor and category index is an essential aspect of calculating the CSI. In this methodology an appropriate weighting tool should be selected based on the scenario that the PTSMAP framework is being used for. Analytical Hierarchical process involving experts, values set by policy, or other tools may be used. Weighting is outside the scope of this research and its absence is discussed in the conclusion of this chapter.

5.9 Application for System Comparison Scenarios

This section outlines how to utilize the PTSMAP framework for system comparison scenarios. For system comparison 1, the default methodology can be followed as described within the preceding sections of this chapter. This methodology is detailed in chapter 5 with a sample data set in order to demonstrate research question 1 and explore research question 2.

For system comparison 2, the following process can be followed:

- **Part 1:** benchmark values are loaded into the framework as a "benchmark system". These values are treated the same as data from any other system.
- **Part 2:** the benchmark system is used in the calculation of factors for all systems involved in the study. For both the z-score and utility methods the benchmark values are treated as a "system" for the calculation of all category indices.
- **Part 3:** CSI values are calculated for each system, including the benchmark system. The systems are ranked based on index enabling direct comparison to the benchmark values.

When conducting a system comparison scenario, all weights for all factors and categorical indices should be equivalent – for example, across all systems the same value for GHg emission weighting should be used. In decision making scenarios, which look at one system or geographic context, an individual set of weights that re based on expert opinion, policy, or other evidence should be used.

System comparison 2 is not addressed directly within this research, but could be used by transit authorities, consultants, or future researchers in exploring the use of the PTSMAP framework or an expanded framework to better develop sustainable mobility through transit systems.

5.10 Applications for Decision Making Scenarios

Previously the framework has been discussed in terms of calculating CSI values for researching how different modes contribute to sustainable mobility, next the framework's use in decision making will be discussed. The PTSMAP framework can be applied for researching public transit sustainability but also for improving how decision makers select transit system improvements. The overall framework follows the principles set out by Gwo-Hshiung & Jih-Jeng in 2011 for a Multiple Attribute Decision Making Process. The parallel structure of the PTSMAP framework's approach compared to the 5 step approach set out by Gwo-Hshiung & Jih-Jeng (2011) is set out in Table 5-15.

Table 5-15 Alignment between MADM and PTSMAP

Gwo-Hshiung & Jih-Jeng	**PTSMAP approach**
Step 1: Define the nature of the problem	Literature Review of Sustainable Mobility Principles
Step 2: Construct a hierarchy system for its evaluation	Selection of indicators for research project.
Step 3: Select the appropriate evaluation model	Development of PTSMAP framework using literature review information. Indicators are selected using current research.
Step 4: Obtain the relative weights and performance score of each attribute with respect to each alternative;	In this study, use of default weights, in practice AHP or other decision tools may be used. Application of PTSMAP framework part 2 and 3 to calculate indices – categorical and CSI to aid in understanding how alternatives compare to one another.
Step 5: Determine the best alternative according to the synthetic utility values, which are the aggregation value of relative weights, and performance scores corresponding to alternatives.	Ranking of systems by CSI or categorical index values to determine which alternative has the desired sustainability performance.

The application of the PTSMAP framework to the two decision making scenarios varies based on scenario specification as well as the nature of the application of the PTSMAP framework. The following two sections outline the application of the methodology.

5.10.1 Applications for Decision Making Scenario 1

Applying the PTSMAP framework for decision making without benchmark criteria can be utilized in two ways – in both cases forecasted performance is required:

1. Deciding between a set of discrete alternatives for developing a transit system irrespective of the system's overall performance to a broader set of transit systems (such as other transit systems in the country or the world).
2. Considering how the set of transit system improvements would improve the system's sustainable mobility relative to other systems.

Method 1 is used when the decision maker only desires to know which system alternative has the strongest CSI performance relative to the set of alternatives. It does not comment on the broader impacts choosing an alternative on the system's overall sustainability – for example selecting a particular LRT expansion out of several options for an existing LRT network - nor does it allow further discussion on the alternative's performance due to a lack of benchmarks or comparison to other systems.

The methodology is relatively simple and the framework described in this chapter can be followed as it is outlined. Regardless of if the z-score or utility method is employed in part 3, CSI scores are then calculated and used to inform the decision making process, with higher scored systems being preferable to achieve sustainability goals.

For application 2, an adaptation of the default PTSMAP framework described in this chapter is required. This methodology is used when a decision maker wishes to see how a transit system improvement can improve sustainable mobility compared to existing mass transit systems. This methodology requires more data than the previous methodology, however it shares greater insight into how the system performs relative to a larger range of transit systems. The adapted methodology is operated as follows:

- **Defining the problem -** for a decision making problem with n plan alternatives there will be n runs of the PTSMAP framework comparing each alternative to a set of j systems. For alternatives that will expand an existing system, an initial step should be run that will calculate the system's default CSI value relative to all j systems.
- **Considering factors -** for a plan alternative that connects to an existing mass transit system (i.e. an expansion) add all forecasted values to existing data (i.e. GHg emission forecasts to existing, revenue forecasts to historic revenue), for a new system treat all factors as a discrete system.
- **Calculating the CSI** – calculate the CSI as in the default framework using either the z-score or utility approach.

Once the initial CSI values are calculated the plan alternatives can be evaluated based on the PTSMAP framework. For system alternatives that are an extension to an existing mass transit system, the alternative that yields the greatest improvement relative to the set of j existing systems is most favourable in the PTSMAP framework. For alternatives that are not an extension, the highest ranking alternatives are most favourable.

Method 1 is demonstrated in chapter 6 using Translink data from an on-going study for mass transit expansion.

5.10.2 Applications for Decision Making Scenario 2

Decision Making Scenario 2 follows a similar set up to Decision Making Scenario 1 with one exception: the inclusion of benchmark values, either from policy, research, or other sources that are included as an additional system in the calculation of CSI values through all parts of PTSMAP framework.

5.11 Comparison to Past Studies

In the literature review, past transportation sustainability studies were reviewed and analyzed in order to inform the development of this methodology.

5.11.1 Kennedy 2002

Kennedy 2002 informed this methodology through its use of historic and model data in an impact based framework to research how different modes (public and private) contribute to sustainable mobility in the Toronto area. The characterization of private and public transit as different travel systems, which can be compared through different sustainability categories based on indicators and available data, informed the development of this methodology as shown through the category and factor selection in this framework. However, this methodology's focus on comparing multiple public transit systems has limited the factors to those pertinent to public transit. Kennedy's study also looked at broader economic integration at greater detail using data available to the Toronto area. This study's scope has focussed on comparing a larger sample of systems at lower resolution and has thus neglected some of the factors included in Kennedy's work. Unlike Kennedy's study, this work presents a methodology to calculate composite indices.

5.11.2 Jeon 2007, Jeon et al 2009

Jeon et al 2009 and Jeon 2007 both demonstrate how to use an expanded impact based framework along with model outputs and a utility methodology to calculate a composite sustainability index and utilize it for research purposes into decision making. The indicators for these studies were focused on the broader transportation network, with a special attention given to automobile networks, and were more specific to the goals of the Atlanta region. This study aims to create a transit specific framework that is not specific to any given context. The CSI structure and four categories are the same between frameworks, along with the weighting structure.

5.11.3 Haghshenas & Vaziri 2012

Finally Haghshenas & Vaziri's 2012 study of global cities and their transportation systems presented a final methodology for sustainability analysis which informed this approach. The approach from 2012 focussed on using specific transportation factors to assess overall transport systems' ability to contribute to sustainable mobility using a global data base. A similar formulation is used in this methodology, including the use of a CSI and weighted sum equation. However, this study is focussed on the comparison of transit systems and inasmuch transit specific factors have been selected along with the inclusion of system effectiveness as a fourth category of sustainability as was done by Jeon 2007 and Jeon et al 2009.

5.12 Conclusion

This chapter presents a 3 part framework, the PTSMAP Framework for assessing how public transit systems contribute to sustainable mobility. This framework first guides the selection of data through categories and factors. Then it outlines how to normalize and formulate the data for development of category indices and finally composite sustainability indices. This chapter also presented a selection of factors for each category along with potential data sources and relevant discussion on their use in sustainability analysis. Chapter 6 utilizes this methodology using data from the National Transit Database to demonstrate its use and also explore research question 2.

Chapter 6: Application of Mass Transit Composite Sustainability Assessment

6.1 Chapter Overview

Chapter 6 demonstrates a direct application of the PTSMAP framework in order to show its utility for researching public transit sustainability as well as to provide insight into the second research question of this thesis project: what are the relative contributions to sustainable mobility of different mass transit modes? This chapter begins with a discussion of data and factor selection, based on the methodology of the PTSMAP framework, which includes an overview of how data was sought out for this project and which data sets were considered to demonstrate the framework's utility as well as explore the research question. Next, the chapter outlines how 33 heavy and light rail transit systems from the National Transit Database (NTD) were treated and expanded for utilization under each set of factors – environmental, economic, social, and system effectiveness. Next, the results of each sustainability category are discussed in comparison to past research. Continuing, the chapter shares composite sustainability indices based on the methods and techniques outlined in chapter 5 and comments on the relative ranking of the 33 transit systems. Analysis is also provided based on how urban factors such as density relate to individual category indices, as well as overall CSI values. Next, a sensitivity analysis is outlined where weighting values have been adjusted for category indices in the calculation of CSI values. This analysis demonstrates how different policy scenarios can change the CSI and also shows how this research could be expanded through the inclusion of decision tools, such as analytical hierarchy processes, to inform weighting. Finally, the chapter shares overall conclusions, limitations, and opportunities for further research.

6.2 PTSMAP Part 1: Data Discussion and Factor Selection

The first section of this chapter is concerned with the application of part 1 of the PTSMAP framework and the collection of suitable data to explore research question 2.

6.2.1 Available Data

To conduct a study that compares multiple mass transit systems based on primary mode, for example LRT, BRT, heavy rail, a large data set is required that contains information on a variety of indicators. The factors specified in the methodology cover a range of information that reflect public transit interaction with sustainable mobility, as defined through the literature review, and represent a thorough study. However, in reality, complete data may not always be readily available, which can hinder the direct application of this methodology. It is important to note that the PTSMAP is modular and appropriate proxy factors may be utilized in the place of the factors presented in the methodology. When analyzing systems, some proxy factors may be used when direct data is not available, or data may need to be expanded to generate a representation of a factor using analytical modelling or other techniques.

Given the scope of this PTSMAP framework, several data sets were reviewed to find a set with a large enough quantity of systems as well as enough breadth of data to utilize the PTSMAP framework's indicator set. In addition to data sets, transportation agencies in a variety of geographic contexts were contacted with data requests to construct an alternative database. Due to low rate of reply, open data sets were pursued over a constructed data set.

6.2.2 NTD

The National Transit Database is a comprehensive dataset updated annually in the USA that contains operational information for all transit systems that receive federal funding (Department of Transportation, 2013). Over 660 transit providers and agencies submit data to this internet based database making it an invaluable tool for research and planning purposes. The database is mandated by congress and maintained by the Department of Transportation, while the data is submitted by agencies across the USA independently – inasmuch, the data is not verified by any third party. For research purposes, this data set was deemed adequate for the following considerations:

- **Breadth of data**: the data set covers a variety of information for several transit related indicators including operational performance, financial information, system overview, and energy consumption based on mode.

- **Quantity of Systems**: the data set includes a large number of systems from a variety of contexts from throughout the United States, which provide excellent opportunity to comment on the relative benefits of different mass transit system modes for providing sustainable mobility.

6.2.3 BRT

Global BRT Data (http://www.brtdata.org/) is an online database produced by EMBARQ and the BRT Observatory in partnership with the International Energy Agency (IEA) and the Integrated Transport Systems and BRT Systems Alliance (SIBRT). As a public database, it contains information on a growing number of BRT systems around the world based on a number of parameters including system length, fuel usage, passengers per day, and bus age. However, at the time of conducting this research, not all systems had a complete set of indicators available, which limited the utility of this data set for a large scale study applying the PTSMAP framework. As the data set grows, it may be used in conjunction with other multi modal datasets to conduct PTSMAP scale studies, however currently only some systems have a wide array of indicator data available so the Global BRT Data set was not selected for this research.

6.2.4 Other Sources

Other data sources were considered for use in this study, including additional national statistics such as the United Kingdom's Department for Transport open statistics site, however similar to the Global BRT data set, they did not have the wide variety of indicators required to complete this study. In particular energy or fuel consumption was a difficult figure to obtain.

6.3 PTSMAP Part 1: Data Selection

6.3.1 Overview of Data

A basic set of data is provided in the NTD dataset which covers several factors reported by transit agencies. For this research, a sub selection of these indicators deemed relevant for sustainability analysis have been selected and listed in Table 6-1. The NTD dataset is composed of numerous spreadsheets where data is stored based on agency. For this research, only agencies that operate LRT and Heavy Rail modes were selected. For these agencies, the indicators listed in Table 6-1 were extracted from their relevant spreadsheets. Note - Imperial units in the database for length, area, and volume (miles, $miles^{2,}$ and gallons) were converted to metric units for this study – km, km^2 , and litres.

Table 6-1 NTD Input Data for Analysis

Data	Units	Symbol	Info
Route Length	Km	L_r	Length of system
Directional Route km	Km	L_d	Length of all directions of route (i.e. a 2 km track with service in both directions is 4km)
Vehicles Operated Max Service	Number of vehicles	n_{op}	The number of vehicles operated during maximum service
Vehicles Available Max Service	Number of vehicles	n_{max}	The number of vehicles available total at max service
Passenger KM Travelled	pkm	pkm	Total annual passenger km travelled on the system
Unlinked Passenger Trips	Trips	τ	Number of passenger unlinked trips on the system
Vehicle or Train Rev km	Km	Vkm	The total km travelled by vehicles during revenue service in the system
Vehicle Or Train Rev Hours	Hours	Vh	The total hours of revenue service for vehicles in the system
Energy for propulsion	kWh	E	The total energy used for

Data	Units	Symbol	Info
			propulsion by the system
Fuel for propulsion	Litres	L	Total volume of fuel used for revenue service
Operating Cost	$	λ	Total operating cost
Revenue	$	r	Fare box revenue
Vehicle capacity	Seats, standing	c	Per vehicle type
Vehicle annual revenue km travelled	Km	ρ	Per vehicle type
Mode		LR or HR	LR is for LRT and HR is for heavy rail transit.

The variables included in Table 6-1 are utilized throughout this chapter within equations for the generation of factors and indices used in sustainability analysis. For future research that compares these NTD systems to other global systems, Table 6-1 can be used for data requests to other agencies or databases where high levels of data are available.

In order to utilize the NTD database for this analysis and thesis project, supplemental data had to be used in some instances. The following sub sections explore the limitations of the data set and how it has been expanded and treated in order to enable a more rigorous sustainability analysis for this thesis project. All data used in this study as inputs is included in Appendix A.

6.3.2 Data Challenges

Sustainability analysis as outlined in chapter 5 requires a large amount of data in order to assess all the dimensions of sustainability and each factor that compose the indices of each dimension. Further, weighting of each factor and each index requires data of its own, either through the use of expert opinion in an AHP or another decision making tool. The NTD provides ample data about transit systems – including operational information, inputs, and outputs useful for sustainability analysis - and it has been employed in past studies. However, it does not provide high resolution data about operations, such as scheduling or vehicle configuration which does not enable further comparison of systems based on capacity utilization. There are other gaps and limitations which prevent a complete sustainability analysis without expansion and treatment, which have been addressed, where possible, within this research.

For most factors, indicators can be estimated by expanding the data with outside data sources or through other data treatment. Given the nature of this research and the depth and breadth of data available within the NTD dataset, despite its limitations, it is still deemed the most appropriate data source to test this methodology and explore the research question.

Throughout this chapter the use of the NTD for each index and the factors associated with it, along with specific limitations for each factor are explored in greater detail. It is important to note two major overall limitations that are not possible to overcome within this research thesis:

1. A complete sustainability analysis between all BRT, LRT, and heavy rail or metro is not possible with the NTD due to the fact that data for BRT is not available at present. Therefore this analysis will focus on comparing LRT and heavy rail modes.
2. A complete analysis as described in the preceding chapter has been attempted, although some omissions have been made due to data and technical limitations within this dataset and research. These limitations can be removed with further research or data collection that are outside of the scope of this study.

33 systems were utilized in this study – 13 heavy rail (coded HR) and 20 LRT (coded LR). These do not include all systems coded as HR and LR within the data set. For the remainder of this chapter, LRT will be referred to as LR and heavy rail will be referred to as HR to keep consistency with the NTD dataset.

Systems that operate as a streetcar type service are included in the LR designation and have not been included in data set due to this study's focus on mass transit comparison and understanding how each system mode is able to realize sustainable mobility benefits. Systems that do not operate in an urban context/serve a contiguous dense metropolitan area or are intended to function as a connector for spread out cities, such as the Sprinter system in California were removed from this study as the focus of this study is on urban mass transit systems. In some cases, mass transit systems have been removed due to challenges in data interpretation that could not be overcome with this methodology. Of particular note, the New Jersey Transit Corporation light rail systems are not included in the analysis as it would appear the diesel powered River Line's data is included with the other systems operated by this operator. The River Line would not be included in this study because its service is similar to Sprinter in that it can also be characterized as an intercity service with stops serving smaller communities between.

Table 6-2 Systems Selected for Analysis outlines the systems included within this study as well as their system ID in the NTD database:

Table 6-2 Systems Selected for Analysis

	System ID	Operator Name
HR	1003	Massachusetts Bay Transportation Authority
	2008	MTA New York City Transit
	2098	Port Authority Trans-Hudson Corporation
	2099	Staten Island Rapid Transit Operating Authority
	3019	Southeastern Pennsylvania Transportation Authority
	3030	Washington Metropolitan Area Transit Authority
	3034	Maryland Transit Administration
	4022	Metropolitan Atlanta Rapid Transit Authority
	4034	Miami-Dade Transit
	5015	The Greater Cleveland Regional Transit Authority
	5066	Chicago Transit Authority
	9003	San Francisco Bay Area Rapid Transit District
	9154	Los Angeles County Metropolitan Transportation Authority
LR	0008	Tri-County Metropolitan Transportation District of Oregon
	0040	Central Puget Sound Regional Transit Authority
	1003	Massachusetts Bay Transportation Authority
	2004	Niagara Frontier Transportation Authority
	3022	Port Authority of Allegheny County
	3034	Maryland Transit Administration
	4008	Charlotte Area Transit System
	5015	The Greater Cleveland Regional Transit Authority
	5027	Metro Transit
	6008	Metropolitan Transit Authority of Harris County, Texas
	6056	Dallas Area Rapid Transit
	7006	Bi-State Development Agency
	8001	Utah Transit Authority
	8006	Denver Regional Transportation District
	9013	Santa Clara Valley Transportation Authority
	9015	San Francisco Municipal Railway
	9019	Sacramento Regional Transit District
	9026	San Diego Metropolitan Transit System
	9154	Los Angeles County Metropolitan Transportation Authority
	9209	Valley Metro Rail, Inc.

6.4 PTSMAP Part 2: Data Treatment and Expansion

The following sub sections demonstrate data treatment and expansion for each category for the NTD dataset for the PTSMAP framework. As data specific methodologies are required for some expansions they are described and outlined where necessary along with required literature references.

6.4.1 Data Treatment and Expansion: Environment

Within the dataset, the major environmental information available is energy or fuel required to operate the system on an annual basis. The other factor that can be related to the environmental index is system length, which can be tied to the environment disruption factor.

When conducting sustainability analysis, the first factor considered for the environmental index is the energy factor. The NTD raw data provided data in terms of kWh utilized per each system for propulsion of vehicles per year of operation which may be used as an indicator for sustainability analysis when normalized to a MJ/pkm basis. This is a unit conversion and normalization calculation that is conducted as follows. Given:

$$1\,W = 1\frac{J}{S} \quad \text{therefore} \quad 1\,kWh = 3.6MJ$$

$$E_{Ej} = \frac{3.6E_j}{pkm_j}MJ$$

Where E_{Ej} is the environmental factor for energy consumption per passenger kilometer travelled for system j in units of MJ/pkm.

The second set of factors for the environmental index is pollution oriented. From the methodology chapter, there are two types of pollution – noise and emission of pollutants such as gasses and particulate matter. Unfortunately, for this study noise cannot be qualified or quantified due to a lack of available data within the NTDB so it has been omitted from this analysis. While resources exist, such as the Department of Transportation's 2006 Transit Noise and Vibration Impact Assessment Manual, which can help quantify the impact of noise given a wide range of input data, the NTDB does not provide appropriate input information for these techniques.

The NTDB does not provide direct information on emissions from individual systems; the data can be expanded in order to use information on energy usage to approximate emissions. A simple spreadsheet model has been developed that is consistent with techniques used by Vincent and Walsh (2003) and Puchalsky(2005) for expanding energy data from rail systems in the USA in order to comment on the emissions of these systems. As outlined in chapter 4, these authors utilized the NTDB to determine overall energy utilized by particular transit systems and then used a state level emissions factor table to determine the emissions of the modes they were comparing, in the case of their research BRT and LR (Vincent & Walsh, 2003) (Puchalsky, 2005).

The Emissions & Generation Resource Integrated Database (eGRID) is an inventory of environmental attributes of all electrical generating plants in the USA (E.H. Pechan & Associates, Inc., April 2007). The current eGrid dataset contains emission rates for 2007, which Leonardo Academy Inc. has prepared in its white paper for use in a variety of contexts. While these rates do not match the 2010 year used in the NTD data used for this study, they do provide the temporally closest emission rates out of any available data set and are considered appropriate for calculating emission estimates for this study. It is assumed that for this analysis these rates are acceptable and in future studies up to date estimates can be plugged into the analytical framework.

This model was created using a table from a Leonardo Academy Inc. white paper, which was generated in 2011 from a 2007 United Stated Environment Information Administration (EIA) eGrid data set (Leonardo Academy Inc., 2011). These factors take into account a base loss of 5.9% due to transmission and distribution and are based on 2007 data, which is the latest official e-Grid data available from the USA EIA. The eGrid data set provides information and data on emission rates for regions and states in the USA and the Leonardo Academy Inc. white paper synthesizes the rates into an easy to use table for the development of models and equations.

Essentially, the model used in this thesis multiplies state level emission factors by the kWh system data provided in the NTD dataset. In turn, these factors are based on the emission averages that are in turn based on electricity generation mixes (Leonardo Academy Inc., 2011) (E.H. Pechan & Associates, Inc., April 2007).

This data expansion methodology can be expressed mathematically as follows in Equation 6-1:

Equation 6-1 Emissions Factor Calculation

$$E_{pj,i} = \frac{f_{j,s} c_{s,j,i}}{pkm_j}$$

(adapted from Puchalsky, 2005)

- Where E_p is the quantity of emissions of pollutant i for system j;
- Pollutant i represents either greenhouse gases or local pollutants
- and f is the quantity of energy or fuel consumed by system j in state s;
- and c represents the emission factor for pollutant i in state s

For greenhouse gases, a CO2 equivalency factor is included in the calculation known as global warming potential. These values are obtained from work by Forster et al (2007) for the IPCC . e-GRID includes the following greenhouse gases: CO_2, NH_4, N_2O and values from the IPCC in this research. The values from Forster et al reflect the global warming potential of a particular gas relative to CO_2. These GWP factors allow a single CO2E mass to be calculated for each transportation system involved in this study through Equation 6-3:

Equation 6-2 CO2 Equivalency Equation

$$\text{mass CO2 Eq.} = \text{(mass of gas) (GWP)}$$

Adapted from (Forster, et al., 2007).

Table 6-3 outlines the global warming potentials utilized in this study as well as other global warming potentials outlined by Forster et al.

Table 6-3 Global Warming Potential for Common Greenhouse Gasses

		Global Warming Potential for Given Time Horizon			
Greenhouse gas	**Chemical Formula**	**SAR (100-yr)**	**20-yr**	**100-yr**	**500-yr**
Carbon dioxide	CO_2	*1.00*	*1*	*1*	*1*
Methane[c]	CH_4	*21.00*	*72*	*25*	*7.6*
Nitrous oxide	N_2O	*310.00*	*289*	*298*	*153*

Adapted from Forster et al (2007).

For NH_4 and N_2O the SAR or second annual assessment report values have been utilized when calculating the GWP and CO2 eq values for this study based on the application of these values in the Kyoto Protocol (Forster, et al., 2007). The second set of GWP 100 year values represent values that are the product of more recent research in climate science, chemistry, and atmospheric science. GWP values are continually updated as research progresses, which is why the SAR values were integrated into the Kyoto protocol in order to give a set level for standardized calculations. In future research the updated values may be applied – however, given that the same set factors are applied to all systems, for the comparison of general global warming potential between HR and light rail systems, as well as environmental impact more broadly and the development of a CSI, the differences between the two sets of values is deemed negligible within the scope of this research.

This methodology uses different emission factors for each state based on grid calculations for electricity. These factors are included in Appendix B. If fuel based vehicles were to be used, fuel standards would take the place of grid emission rates – no BRT systems or LR or HR systems that use fuel were included in this set of analyses so fuel is included for the sake of discussion only.

The final environmental factor, land consumption, is also not readily utilized given the NTD dataset. While data on system length is included, finding a meaningful way to utilize this data requires further information on the specific geographic context of the cities themselves. Impacts on land and natural environment by each system are not readily discerned from available data without external data. Within the scope of this study, there are not any specific expansions to the data that could be carried out to directly compare each system.

Based on data limitations and possible expansions, the factors that are utilized within this research for the calculation of the environmental index are listed below in Table 6-4 Environmental Factors.

Table 6-4 Environmental Factors

Factor	Description
E_{Ej}	Energy consumed by system j per passenger km travelled
E_{gj}	CO2 equivalents system j per passenger km travelled
E_{SO2j} $E_{NOX\ j}$ $E_{HG\ j}$	Local emissions per passenger km travelled

6.4.2 Data Treatment and Expansion: Economy

In the literature review and methodology section it was discussed that the economic index and the factors that comprise it are more common elements of transportation planning and engineering and rely on more readily available data. This holds true for the NTD dataset. The basic data used from the NTD set includes total operating costs and total revenue, as well as other operational data which can be used to calculate a number of factors for the calculation of the economic index.

The first factor under the economic index used in this study is operating cost, which is normalized by dividing by pkm. Operating costs are broken down in the NTD data set based on several categories for reporting purposes. For this research, total operating cost is required so these sub categories are summed. Capital costs are not used in this study for reasons discussed in preceding chapters, as well as a lack of data in the NTD. The NTD only contains capital data for the year of the data set, which does not reflect the needs of this study so it has been omitted. Operating costs can be considered as followed in Equation 6-3:

Equation 6-3 Operating Cost Factor Equation

$$N_{o,j} = \frac{\lambda_j}{pkm_j}$$

- Where λ_j represents the operating costs of system j;
- pkMJ represents the annual passenger kilometres travelled on system j;
- and $N_{o,j}$ represents the factor for operating costs per passenger kilometer travelled on system j

The next set of factors are: 1) user costs, which are represented by average fare and 2) average travel time. Average fare is calculated by dividing the annual revenue from fares by the total annual revenue trips. This is shown in Equation 6-4:

Equation 6-4 Average System Fare Factor Equation

$$N_{f,j} = \frac{r_j}{\tau_j}$$

- Where r is the revenue for system j;
- τ_j is the total unlinked trips for system j;
- and $N_{f,j}$ represents the factor for average fare on system j

Average travel time is calculated using the system wide average for vehicle travel speed (a system effectiveness factor) as well the average trip length. Average trip length is based on annual passenger kilometers travelled in the system divided by total trips. Calculation of travel speed is a multi-step process which is explored in the data treatment section for system factors. Average passenger km per trip travelled is divided by average speed to calculate average travel time as displayed in Equation 6-5.

Equation 6-5 Average Travel Time Cost Factor Equation

$$N_{t,j} = \frac{\frac{pkm_j}{\tau_j}}{v_j}$$

- Where pkm is the passenger km travelled for system j;
- τ is the total unlinked trips for system j;
- v_j is the average velocity of transit vehicles for system j;
- And $N_{t,j}$ represents the factor for average ravel time on system j

Recovery of costs is calculated using two pieces of data from the NTD dataset without expansion or manipulation: total operating cost and total fare revenue. The output of this calculation is expressed as a percentage and requires no additional treatment. The economic recovery factor is shown in Equation 6-6.

Equation 6-6 Recovery Factor Equation

$$N_{z,j} = \frac{r_j}{\lambda_j}$$

- Where r_j is the revenue for system j;
- λ_j is the total operating costs for system j;
- And $N_{z,j}$ represents the factor for recovery on system j

Percent of costs subsidized or funded through agencies or government sources cannot be determined readily with the current dataset so it is omitted from this study. Transit's usage relative to economic activity as represented with pkm/GDP is the final factor considered and is calculated using basic input data as well as an expansion using GDP for the metropolitan statistical area served by the system as provided by the US Department of Commerce. The calculation of transport activity relative to economic activity is shown in Equation 6-7.

Equation 6-7 Transport-Relative to Economic Activity

$$N_{g,j} = \frac{pkm_j}{\mathrm{GDP}_j}$$

- Where pkm_j is the passenger km travelled for system j;
- gdp_j is gross domestic product of the host urban area of system j;
- And $N_{g,j}$ represents the factor for transit economic interaction for system j

Based on the limitations in the data set only 5 factors in the economic category are utilized in this study. To summarize, they are displayed in Table 6-5.

Table 6-5 Economic Factors

Factor	Description
$N_{o,j}$	Operating costs per passenger km travelled on system j.
$N_{f,j}$	Average fare per trip on system j.
$N_{t,j}$	Average travel time cost per trip on system j.
$N_{z,j}$	Cost recovery on system j.
$N_{g,j}$	Transit use per economic activity on system j.

6.4.3 Data Treatment and Expansion: Social

The NTD data set presented challenges for calculating a complete set of social indicators as presented in other studies particularly with respect to health impacts due to the lack of high resolution data on particular routes. The NTD data set's strength is in providing a large amount of data on a large number of systems, however, high detail data is not available, which does limit the ability of some aspects of the PTSMAP framework inquiry. Due to this health factors related to emissions as well as death and injury are not included in this study.

The first two factors considered are abstractions of the user's ability to access the system. Factor one was utilized by Haghshenas & Vaziri (2012) for calculating how different transport modes enable access throughout global cities. In this research, the indicator has been adopted for comparing transit system accessibility. The factor is passenger km travelled per capita per unit of urban area. This factor has been adopted for this study for two reasons. First, it is a measure of accessibility that can be calculated using data from the NTD data set. Second, as per the definition of the factor – it shares on average how many km per person originate per unit of urban area - it is a decent indicator of the ability of the transit system to enable connectivity and access through the city.

It is important to note that the definition of urban area used in this research was a point of concern. In the NTD urban areas are provided as UZA or Urbanized Area, which is based on the 2000 US Census (Federal Transit Administration, 2013). The NTD also provides areas as service areas. However, service areas mix bus and rail routes so this value is not immediately useful for this mass transit inquiry. More nuanced data could be used in future studies as it could be argued that feeder bus service to mass transit stations could be counted as increased accessibility, although a discussion of transfer penalties would need to be included.

Data from the US census for population and urban area was also collected for urban areas and populations to be used in the calculation of this indicator in addition to what was provided by the NTD. This step is included for some systems that do not explicitly serve multiple cities within a larger metropolitan area. For example, New York MTA is listed as serving New York-Newark, NY-NJ-CT, a broader metropolitan area. However, the subway system itself only serves New York city meaning that the values for population and area included with the NTD data will not represent the subway's accessibility accurately. Other systems have further challenges with this factor, such as Port Authority Trans-Hudson Corporation (PATH), which serves multiple cities and according to the NTD reported data would therefore have a large population and area for this factor (New York-Newark, NY-NJ-CT). These challenges are unavoidable when working with high level data and indicators that measure accessibility at a high level.

The distinction used in this thesis for deciding whether to use city population and area values from the census or larger UZA area representing metropolitan areas from the NTD dataset itself is as follows:

- Utilize the NTD dataset provided values for systems that serve cities and their surrounding areas based on terminus of the system or serves a wider area (LA Metro)
- Utilize specific urban area when the mass transit system explicitly ends within a city boundary (MTA New York)
    - For the Staten Island Railway, Census Bureau Data for the Borough of Staten Island is used as this system explicitly only serves this borough of the city
- Add up urban areas for systems that cross between major cities (e.g. PATH).

The general calculation approach for this accessibility factor is shown in Table 6-8.

Equation 6-8 Accessibility Factor Equation

$$S_{a,j} = \frac{\frac{pkm_j}{population_j}}{\text{urban area}_j}$$

- Where pkm_j is the passenger km travelled for system j;
- $population_j$ is the population of the host urban area of system j;
- urban area_j is the urban area of system j as described above;
- And $S_{a,j}$ represents the factor for accessibility for system j

The next accessibility related indicator is average journey length which is simply calculated through the division of total passenger km travelled by total unlinked trips. This factor represents the length of travel users must take to reach activities (either personal, employment, or residential) – due to the high level nature of the data used in this study it is a second measure of accessibility used in conjunction with system accessibility. Higher scores on this factor indicate that users must travel further on average to reach their activities, indicating the system and land use of the region it serves are not as integrated or that the system has lower user accessibility. However, the factor is a high level proxy for accessibility and future studies should consider a complete accessibility indicator. Average journey length is calculated by Equation 6-9.

Equation 6-9 Average Journey Length Factor Equation

$$S_{l,j} = \frac{pkm_j}{\tau_j}$$

- Where pkm_j is the passenger km travelled for system j;
- τ_j is the total trips for system j;
- And $S_{l,j}$ represents the factor for average journey length for system j

The next factor considered in this application of the methodology is affordability as expressed by average fare divided by income per capita. While average fare represents the direct cost a user pays for the system, this factor represents the quantity of an individual's income they must utilize for a trip on the system and therefore another degree of access or affordability of the system. Where average fare per GDP per capita is calculated by dividing fare revenue by total unlinked trips, and dividing the result by income per capita as recovered from the American Census Fact Finder Website. The affordability factor can be calculated using Equation 6-10.

Equation 6-10 Affordability Factor Equation

$$S_{f,j} = \frac{\frac{r_j}{\tau_j}}{income_m}$$

- Where r_j is the fare revenue for system j;
- τ_j is the total unlinked trips for system j;
- $income_m$ is the income per capita in the MSA serviced by the system operator as stated by the American Census (contained in Appendix C);
- And $S_{f,j}$ represents the factor for average fare per GDP per capita for system j

The final social factor considered in this study is user accessibility, which is based on local accessibility of stations and vehicles for users with physical disabilities. The NTD database contains data on the number of stations for each system that are compliant with the Americans with Disabilities Act of 1990. According to the NTD website, ADA compliant stations are those that do not restrict access for individuals with physical disabilities, including those with wheel chairs, while providing ready access without physical barriers (Federal Transit Administration, 2013). The percentage of stations within a system that satisfy the ADA definition requirements based on NTD reporting definition is adopted for this research as the metric for the user accessibility factor. Within the NTD dataset, information on the number of ADA compliant stations as well as the total number of stations is available. This factor is simply calculated by Equation 6-11.

Equation 6-11 User Accessibility Factor Equation

$$S_{u,j} = \frac{stations_{ada,j}}{stations_j}$$

- Where $stations_{ada,j}$ is the number of ADA compliant station on system j;
- $stations_j$ is the total number of stations on system j;
- And $S_{u,j}$ represents the factor for user accessibility for system j

Based on the limitations for the data set selected for this analysis, only 4 factors can be used for this inquiry. To summarize, the 4 social factors are contained in Table 6-6 Social Factors.

Table 6-6 Social Factors

Factor	Description
$S_{a,j}$	Accessibility factor for system j.
$S_{f,j}$	Average fare / income per capita for system j.
$S_{l,j}$	Average travel length per trip for system j.
$S_{u,j}$	% of stations that are ADA compliant on system j.

6.4.4 Data Treatment and Expansion: Effectiveness

System effectiveness factors represented in the PTSMAP framework are capacity utilization and trips per capita. Mode split data is not available in the NTS data set so this factor has not been included in the study.

The first factor, capacity utilization is a more involved calculation process than other factors in the NTD dataset which involves two steps that manipulate data from vehicle utilization in the NTD dataset.

First, as the capacity of a given transit system is not directly reported in the NTD data set, a proxy for capacity has to be calculated using available data. This proxy is called "potential pkm" and is defined as the potential passenger kilometers travelled annually on a given system based on the total number of revenue hours of operation of all vehicles in the given system. This value can be described as a vehicle being filled to capacity for each revenue km it travels. This indicator is an attempt to compare systems on their ability to efficiently utilize the capacity available at their disposal based on available data. This value does not indicate there is necessarily demand to fill this potential pkm nor does it reflect the time of day this unused potential exists in the system. As a thought experiment, this unused potential could exist throughout the day on a consistently used system that has 50% utilized pkm capacity or it could exist due to a system primarily used for peak travel in the am and pm peaks that sees 80% utilization during these times and then sees 20% utilization throughout the day.

The NTD dataset contains records for the capacity of each vehicle type used by each system, along with annual mileage of each vehicle type. These two pieces of information can be used together to calculate the total potential passenger km travelled in a given year, which when used in conjunction with the reported value for annual pkm can reflect how effectively the system uses its potential capacity.

This process is expressed mathematically in Equation 6-12.

Equation 6-12 Potential pkm Calculation

$$pkm'_j = \sum_{x=1}^{y} (c_{x,standing} + c_{x,sitting})(\rho_x)$$

- Where $c_{x,standing}$ and $c_{x,sitting}$ represent the standing and sitting capacities on vehicle type x for system j;
- ρ_x is the total mileage converted to km for vehicle type x on system j;
- x to y is an array of vehicle types unique to system j;
- $population_j$ is the population of the host urban area of system j;
- And pkm'_j is the potential pkm travelled on system j for the year of analysis.

The second step of the calculation is dividing pkm'_j by pkm_j reported to determine a percentage that indicates how much of the potential is used by each system. This process is expressed in Equation 6-13.

Equation 6-13 Capacity Utilization Factor Equation

$$Y_{c,j} = \frac{pkm_j}{pkm'_j}$$

- Where pkm'_j is the potential pkm travelled on system j for the year of analysis;
- pkm_j is passenger kilometers travelled on system j;

- And $Y_{c,j}$ represents the factor for capacity utilization for system j

The next factor utilized in this study for system effectiveness is annual trips per capita served which reflects the number of trips the transit system is able to generate per person in the population served by the system. For this factor, all data is provided by the NTD dataset. This is a simple calculation dividing total unlinked trips by service area population. Equation 6-14 mathematically expresses this process.

Equation 6-14 Trips per Service Population Capita Factor Equation

$$Y_{t,j} = \frac{\tau_j}{p_{s,j}}$$

- Where $p_{s,j}$ is the population served by transit system j;
- τ_j is the total unlinked trips for transit system j
- And $Y_{t,j}$ represents the trips per service population capita for system j

In summary, the system effectiveness factors utilized in this study are contained in Table 6-7.

Table 6-7 System Effectiveness Factors

Factor	Description
$Y_{c,j}$	Capacity utilization factor for system j
$Y_{t,j}$	Trips per service population capita for system j

6.5 PTSMAP part 2: Data analysis and results

In section 6.4 data expansion and treatment methodologies have been outlined for all factors involved in this study. The following sub sections detail the results of calculating individual factors and categorical indices for part 2 of the PTSMAP framework. For each category, factors are calculated for all systems to demonstrate the PTSMAP framework in accordance with research question 1, and comparisons are drawn where possible between LR and HR modes to provide insight into research question 2. To draw comparisons, the maximum, minimum, and average performance for factors are compared along with relevant statistical analysis with accompanying graphs. The percent difference between the two system types for mean, highest, and lowest performance – calculated by the difference between HR and LR divided by the average of both values – is also calculated for all indicators. All systems have been ranked for each factors and sorted into performance categories based on quartiles to aid in analysis.

6.5.1 Environmental Factors

Three environmental factors were calculated for this application of the PTSMAP framework and inquiry into transit system sustainability: energy consumption, contribution to climate change (GHg gas emissions), and environmental emissions.

The first environmental factor, energy consumption, which reflects the energy required by the system per unit of travel required no additional treatment or expansion of data. The NTD database provided propulsion energy in units of kilowatt hours, which have been converted into MJs for future comparison for ease of comparison with other modes on a unit of energy input basis.

The second environmental factor, greenhouse gas emissions, reflects the system's global environmental impact required per unit of travel. It is measured in CO2 equivalents per passenger km travelled and was derived following the methodology described within this chapter based on the energy requirements provided within the NTD and the eGrid methodology as adapted from Leonardo Academy Inc. (2011), Vincent & Walsh (2003), and Puchalsky (2005). These CO2E values are shared in terms of kilograms CO2E emitted per passenger kilometer of travel.

The third environmental factor reflects environmental emissions, which have a range of impacts on atmospheric and ecosystem conditions, that are released due to the energy requirements of public transit . Using the NTD database energy values and the eGrid emissions factors as well as the methodologies as adapted from Leonardo Academy Inc. (2011), Vincent & Walsh (2003), and Puchalsky (2005) values for NOx and SOx emissions for 35 transit systems and Hg values for 33 transit systems have been calculated on a passenger kilometre basis. The values for these three factors are displayed in Table 6-8 Environmental Factors for Heavy and Light Rail Systems.

Table 6-8 Environmental Factors for Heavy and Light Rail Systems

	Operator Name	City	kg CO2E/pkm	kg SO2/ pkm	kg NO_x/ pkm	kg Hg/pkm	MJ/pkm
HR	Massachusetts Bay Transportation Authority	Boston	1.47E-01	4.57E-04	1.24E-04	1.82E-09	0.915
HR	MTA New York City Transit	New York	3.98E-02	1.09E-04	4.10E-05	5.79E-10	0.395
HR	Port Authority Trans-Hudson Corporation	Jersey City	6.14E-02	2.33E-04	6.38E-05	1.15E-09	0.656
HR	MTA Staten Island Railway	New York	1.13E-01	3.08E-04	1.16E-04	1.64E-09	1.118
HR	Southeastern Pennsylvania Transportation Authority	Philadelphia	1.29E-01	1.00E-03	1.92E-04	5.20E-09	0.800
HR	Washington Metropolitan Area Transit Authority	Washington	2.50E-01	8.91E-04	3.80E-04		0.673
HR	Maryland Transit Administration	Baltimore	3.24E-01	2.90E-03	5.55E-04	9.34E-09	1.808
HR	Metropolitan Atlanta Rapid Transit Authority	Atlanta	8.12E-02	5.22E-04	8.96E-05	1.58E-09	0.432
HR	Miami-Dade Transit	Miami	2.07E-01	5.85E-04	3.31E-04	1.70E-09	1.230
HR	The Greater Cleveland Regional Transit Authority	Cleveland	5.40E-01	3.73E-03	9.32E-04	1.43E-08	2.232
HR	Chicago Transit Authority	Chicago	1.04E-01	2.72E-04	1.15E-04	4.00E-09	0.703
HR	San Francisco Bay Area Rapid Transit District	San Francisco-Oakland-Fremont	3.43E-02	2.47E-05	2.33E-05	1.21E-10	0.453
HR	Los Angeles County Metropolitan Transportation Authority	Los Angeles	6.30E-02	4.54E-05	4.30E-05	2.22E-10	0.834
LR	Tri-County Metropolitan Transportation District of Oregon	Portland	3.15E-02	4.84E-05	3.92E-05	2.75E-10	0.574
LR	Central Puget Sound Regional Transit Authority	Seattle	1.84E-02	8.79E-06	2.15E-05	4.65E-10	0.529
LR	Massachusetts Bay Transportation	Boston	1.20E-01	3.75E-04	1.01E-04	1.49E-09	0.751

Operator Name	City	kg CO2E/pkm	kg SO2/ pkm	kg NO_x/ pkm	kg Hg/pkm	MJ/pkm
Authority						
Niagara Frontier Transportation Authority	Buffalo	1.28E-01	3.50E-04	1.32E-04	1.87E-09	1.273
Port Authority of Allegheny County	Pittsburgh	3.36E-01	2.60E-03	5.00E-04	1.35E-08	2.078
Maryland Transit Administration	Baltimore	2.48E-01	2.22E-03	4.25E-04	7.16E-09	1.385
Charlotte Area Transit System	Charlotte	1.45E-01	7.06E-04	1.23E-04	3.16E-09	0.875
The Greater Cleveland Regional Transit Authority	Cleveland	4.44E-01	3.06E-03	7.65E-04	1.18E-08	1.832
Metro Transit	Minneapolis	1.42E-01	3.30E-04	2.82E-04	2.68E-09	0.696
Metropolitan Transit Authority of Harris County, Texas	Houston	1.12E-01	2.12E-04	7.31E-05	2.09E-09	0.640
Dallas Area Rapid Transit	Dallas	2.19E-01	4.15E-04	1.43E-04	4.09E-09	1.252
Bi-State Development Agency	St. Louis	1.42E-01	4.69E-04	1.89E-04	3.39E-09	0.593
Utah Transit Authority	Salt Lake City	2.35E-01	1.60E-04	4.15E-04	9.18E-10	0.907
Denver Regional Transportation District	Denver	1.80E-01	2.51E-04	2.55E-04	1.62E-09	0.744
Santa Clara Valley Transportation Authority	San Jose	7.56E-02	5.44E-05	5.15E-05	2.66E-10	1.000
San Francisco Municipal Railway	San Francisco	6.93E-02	4.99E-05	4.72E-05	2.44E-10	0.916
Sacramento Regional Transit District	Sacramento	7.16E-02	5.16E-05	4.88E-05	2.52E-10	0.948
San Diego Metropolitan Transit System	San Diego	3.49E-02	2.51E-05	2.38E-05	1.23E-10	0.461
Los Angeles County Metropolitan Transportation Authority	Los Angeles	4.87E-02	3.51E-05	3.32E-05	1.72E-10	0.644
Valley Metro Rail, Inc.	Phoenix	8.44E-02	7.27E-05	1.08E-04	1.05E-09	0.535

The first factor, energy required per unit of travel (MJ/pkm), has been calculated for all systems and the systems have been sorted from most to least efficient. The systems have also been sorted into quartile performance categories. These rankings are displayed in Table 6-9.

Table 6-9 Energy Efficiency per Unit of Travel for Heavy and Light Rail Transit Systems

Rank	Operator	Mode	MJ/pkm	Performance
1	MTA New York City Transit	HR	0.39511	Highest
2	Metropolitan Atlanta Rapid Transit Authority	HR	0.43243	LR
3	San Francisco Bay Area Rapid Transit District	HR	0.45308	5
4	San Diego Metropolitan Transit System	LR	0.46117	HR
5	Central Puget Sound Regional Transit Authority	LR	0.52880	3
6	Valley Metro Rail, Inc.	LR	0.53504	
7	Tri-County Metropolitan Transportation District of Oregon	LR	0.57382	
8	Bi-State Development Agency	LR	0.59336	
9	Metropolitan Transit Authority of Harris County, Texas	LR	0.63994	High
10	Los Angeles County Metropolitan Transportation Authority	LR	0.64404	LR
11	Port Authority Trans-Hudson Corporation	HR	0.65585	5
12	Washington Metropolitan Area Transit Authority	HR	0.67271	HR
13	Metro Transit	LR	0.69604	3
14	Chicago Transit Authority	HR	0.70337	
15	Denver Regional Transportation District	LR	0.74351	
16	Massachusetts Bay Transportation Authority	LR	0.75055	
17	Southeastern Pennsylvania Transportation Authority	HR	0.79964	Low
18	Los Angeles County Metropolitan Transportation Authority	HR	0.83372	LR
19	Charlotte Area Transit System	LR	0.87525	5

Rank	Operator	Mode	MJ/pkm	Performance
20	Utah Transit Authority	LR	0.90672	HR
21	Massachusetts Bay Transportation Authority	HR	0.91481	4
22	San Francisco Municipal Railway	LR	0.91612	
23	Sacramento Regional Transit District	LR	0.94755	
24	Santa Clara Valley Transportation Authority	LR	1.00028	
25	MTA Staten Island Railway	HR	1.11819	
26	Miami-Dade Transit	HR	1.23047	Poorest
27	Dallas Area Rapid Transit	LR	1.25190	LR
28	Niagara Frontier Transportation Authority	LR	1.27338	5
29	Maryland Transit Administration	LR	1.38515	HR
30	Maryland Transit Administration	HR	1.80807	3
31	The Greater Cleveland Regional Transit Authority	LR	1.83212	
32	Port Authority of Allegheny County	LR	2.07785	
33	The Greater Cleveland Regional Transit Authority	HR	2.23156	
System Mean			0.93581	

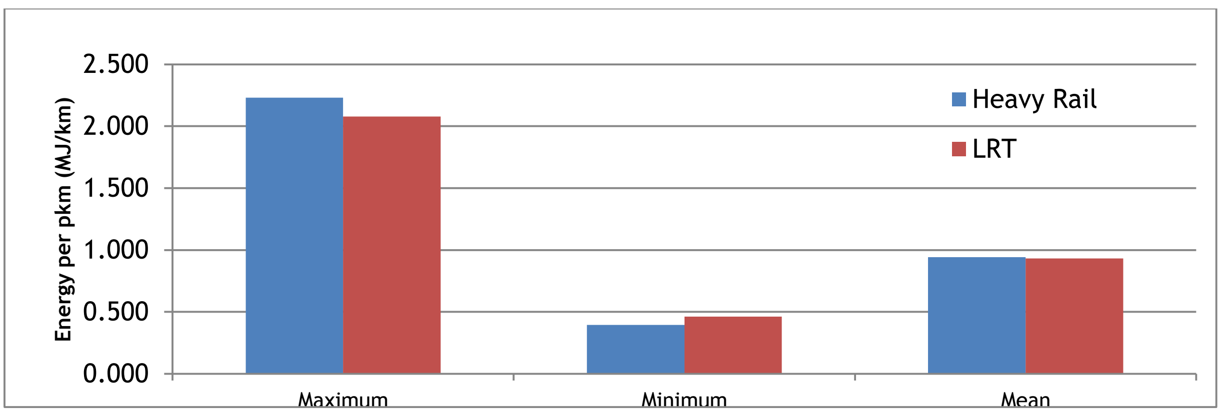
These values have been sorted based on the maximum, minimum, and mean for HR and LR, along with the percent difference of the values in Table 6-10.

Table 6-10 Energy Consumption Ranges for Light Rail and Heavy Rail Transit Systems

	Energy per Unit of Travel MJ/pkm				
	HR		LR		% Difference
Maximum	The Greater Cleveland Regional Transit Authority	2.232	Port Authority of Allegheny County	2.078	7.134%
Minimum	MTA New York City Transit	0.395	San Diego Metropolitan Transit System	0.461	15.430%
Mean	0.942		0.932		1.131%
% Difference max and min	139.83%		127.35%		

These ranges are also graphed for LR and HR transit systems in Figure 6-1.

Figure 6-1 Energy Consumption Ranges for Light Rail and Heavy Rail Transit Systems



As noted in the preceding tables and figure, the maximum and minimum values of energy consumptions for both modes do not vary greatly. In the maximum energy consumption per passenger km travelled case, which represents systems with poorer energy performance, the percent difference is 7.13%, with LR by Port Authority of Allegheny County providing better performance than the Greater Cleveland Regional Transit Authority. The low value demonstrates little disparity between poor performing systems between these modes. When comparing the high performance cases, the HR system, New York (MTA), outperforms the LR system, San Diego Metropolitan Transit system, and the percent difference is 15.43%, which while greater than the less energy efficient systems, is not a pronounced difference.

A t-test was conducted to compare the means of each system with a null hypothesis that the difference of the means of the systems is statistically significant. With a value of -0.047250901 the null hypothesis can be rejected at a 95% confidence interval. When the maximum and minimum values are analyzed in the context of this rejection as well as the value of the percent difference of the means, 1.131% it can be argued that within the NTD dataset systems analyzed on average that there is not a clear distinction between LR and HR systems based on technology/mode choice in terms of energy efficiency for sustainable mobility. In order to further explore energy efficiency, MJ spent by each system and the total passenger pm travelled on each system have been graphed in Figure 6-32 and Figure 6-43. Given the wide range of data, Figure 6-32 is in log scale in order to show the full range of data, while the second focuses on values excluding MTA New York from the displayed range.

Figure 6-2 Passenger Kilometres Travelled and Energy for Propulsion for LRT and HRT Systems

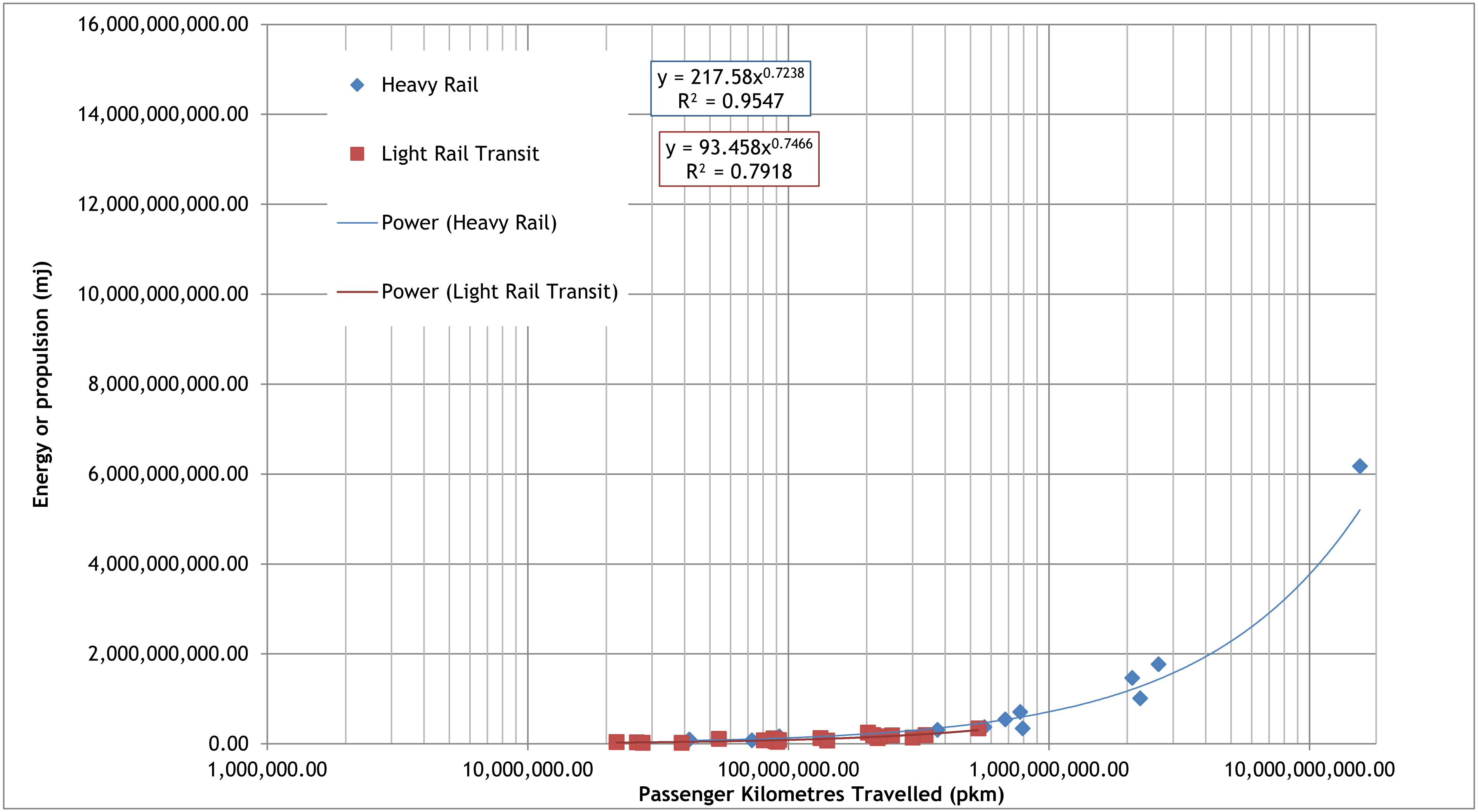
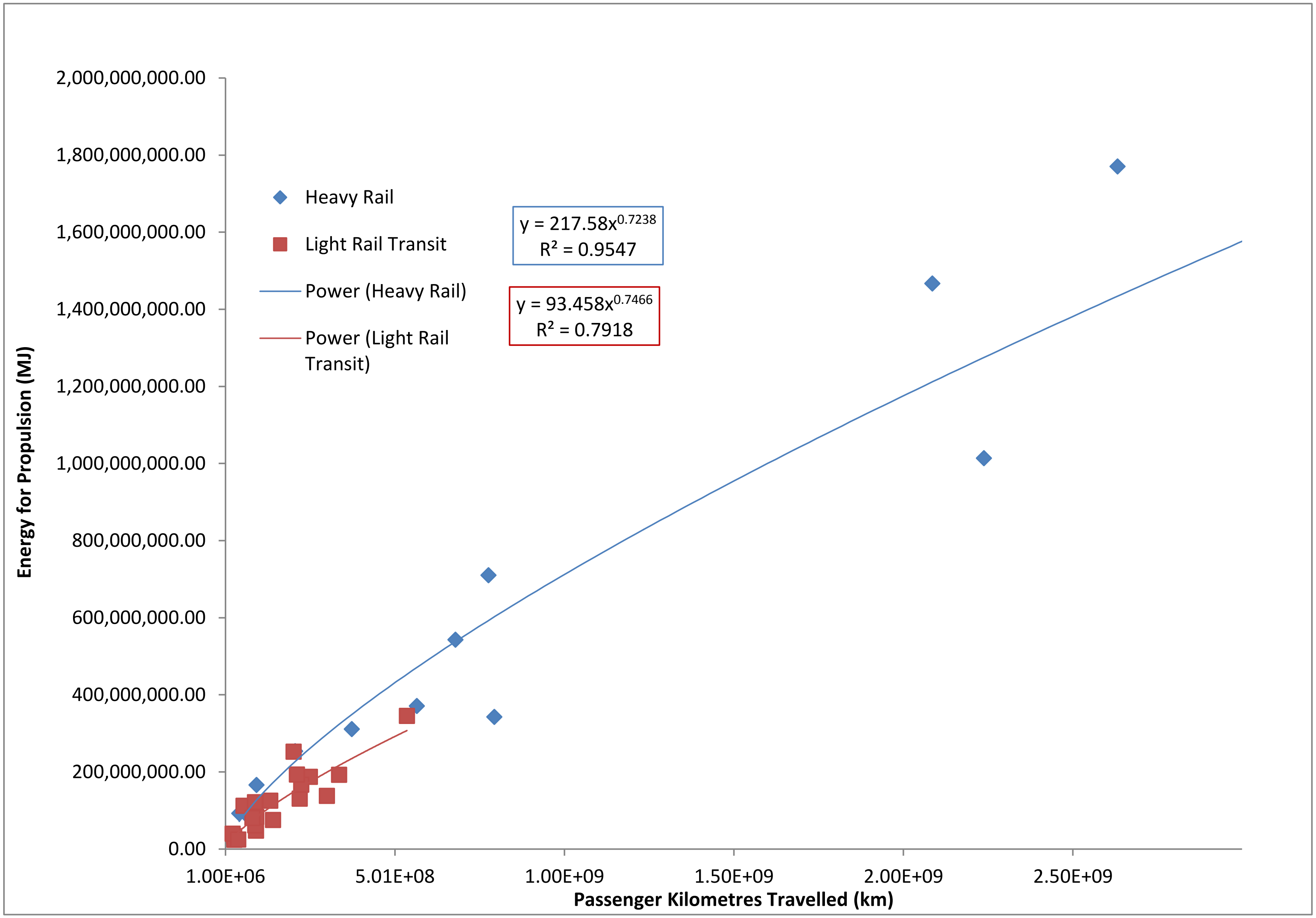


Figure 6-3 Passenger Kilometres Travelled and Energy for Propulsion for LRT and HRT Systems



From the graphs and trend lines, the analysis indicates that there is a an observable trend of LR systems yielding greater energy efficiency results than HR systems. Both trend lines exhibit a high r squared value indicating a high level of fit. However, the threshold for LR was at 536,448,373.64 pkm/year, whereas HR systems served heavier levels of demand and it is uncertain whether the trend can be extrapolated to higher levels of demand for LR. However, for the HR systems that have similar levels of pkm performance, the majority of LR systems provide superior energy efficiency performance. Of the highest performing systems, 5 are LR, although the top three are HR indicating that well planned and efficiently operated HR can outperform LR, although on average LR systems achieve higher energy efficiency. This finding is in alignment with Vuchic (2007) – where it is shared that LRT vehicles typically require lower power per unit space ratings than HR vehicles. From a technical viewpoint, individual vehicles may present energy efficiency benefits due to their mechanical characteristics, capacity, and design features, however system design takes into account other complex considerations, which is what this data represents.

While the maximums and minimums between modes do not vary greatly, within the mode sets of data there is great disparity between the max and min values. For HR, the minimum value for MTA New York differed from The Greater Cleveland Regional Transit Authority by 139.83% , while for LR systems the difference between Port Authority of Allegheny County and San Diego Metropolitan Transit System was 127.35%. Both great differences highlight the need to explore how system factors beyond mode type influence energy consumption.

A suite of operating (i.e. headway, type of vehicle configurations, dwell times, acceleration, etc.), system (i.e. length of system) , and urban factors (i.e. density, supporting land use) may influence energy efficiency per unit travel more than mode choice. This viewpoint is represented in the dataset where operators operate both modes – operators with poor energy efficiency ranking in one mode feature poor energy efficiency in the other mode as well, for example Cleveland has poor energy efficiency in both categories. These factors could be the focus of future study.

When taking a systemic view, this data analysis suggests that both LR and HR systems can achieve similar levels of energy efficiency in the delivery of mobility, although the graphical methods employed in this study do demonstrate higher efficiencies for some LR systems. However, given that the majority of HR systems report higher levels of pkm a direct comparison is not possible.

For the second and third factors, in depth comparison of mode is not provided in this thesis as they are based on factors exogenous to the systems themselves multiplied by the energy consumed by the system – i.e. the power grid emission factors are multiplied by individual system energy consumptions to determine emissions for factors two and three. These emission factors are based on the power available to the systems and are directly calculated from the energy consumption values provided by system operators.

However, given that emissions are a crucial component of the environmental impacts of transportation and therefore an essential element of a sustainable mobility analysis, they are still presented for discussion and calculation of the composite sustainability index. Additionally, if emission reductions are an important goal of system development or expansion, understanding the performance of rapid transit alternatives , benchmarking for comparison to other similar rapid transit systems based on performance can enable more effective decision making. Minimizing emission may be an important policy or master plan strategic outcome so demonstrating the PTSMAP's procedure for evaluating emissions is a crucial element of this study. Finally, factors 2 and 3 demonstrate the dependence of public transit systems on their fuel or energy source on ensuring they achieve desirable environmental performance.

The second factor, greenhouse gases emitted per unit of travel by the public transit systems has been calculated for each system and is displayed ranked smallest to largest by performance levels in Table 6-11.

Table 6-11 CO2E for Heavy Rail and Light Rail Transit Systems

Rank	Operator	Mode	kg CO2E/pkm	Performance
1	Central Puget Sound Regional Transit Authority	LR	0.01837	Highest
2	Tri-County Metropolitan Transportation District of Oregon	LR	0.03153	LR
3	San Francisco Bay Area Rapid Transit District	HR	0.03426	4
4	San Diego Metropolitan Transit System	LR	0.03487	HR
5	MTA New York City Transit	HR	0.03980	4
6	Los Angeles County Metropolitan Transportation Authority	LR	0.04869	
7	Port Authority Trans-Hudson Corporation	HR	0.06143	
8	Los Angeles County Metropolitan Transportation Authority	HR	0.06303	
9	San Francisco Municipal Railway	LR	0.06926	High
10	Sacramento Regional Transit District	LR	0.07164	LR
11	Santa Clara Valley Transportation Authority	LR	0.07563	6
12	Metropolitan Atlanta Rapid Transit Authority	HR	0.08124	HR
13	Valley Metro Rail, Inc.	LR	0.08436	3
14	Chicago Transit Authority	HR	0.10424	
15	Metropolitan Transit Authority of Harris County, Texas	LR	0.11186	
16	MTA Staten Island Railway	HR	0.11262	
17	Massachusetts Bay Transportation Authority	LR	0.12046	
18	Niagara Frontier Transportation Authority	LR	0.12825	Low
19	Southeastern Pennsylvania Transportation Authority	HR	0.12938	LR
20	Bi-State Development Agency	LR	0.14161	5
21	Metro Transit	LR	0.14198	HR
22	Charlotte Area Transit System	LR	0.14472	3
23	Massachusetts Bay Transportation Authority	HR	0.14682	
24	Denver Regional Transportation District	LR	0.17980	

Rank	Operator	Mode	kg CO2E/pkm	Performance
25	Miami-Dade Transit	HR	0.20701	
26	Dallas Area Rapid Transit	LR	0.21883	Poorest
27	Utah Transit Authority	LR	0.23495	LR
28	Maryland Transit Administration	LR	0.24823	5
29	Washington Metropolitan Area Transit Authority	HR	0.25009	HR
30	Maryland Transit Administration	HR	0.32402	3
31	Port Authority of Allegheny County	LR	0.33618	
32	The Greater Cleveland Regional Transit Authority	LR	0.44355	
33	The Greater Cleveland Regional Transit Authority	HR	0.54026	
System Mean			0.15088	

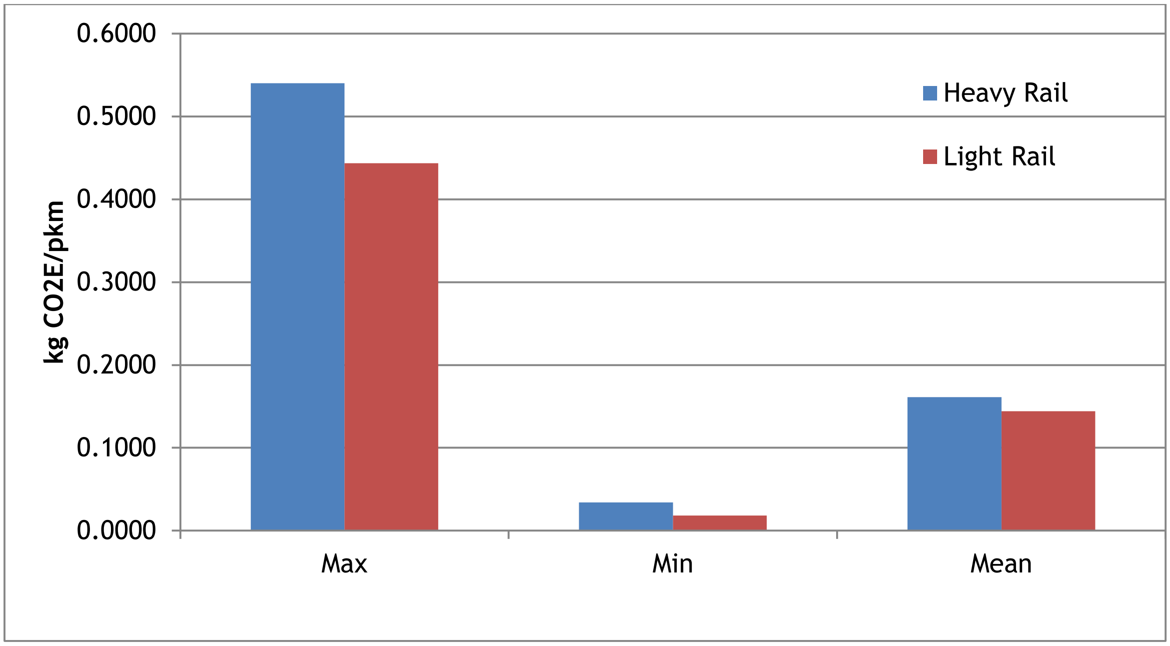
These values have also been segmented into maximum, minimum and mean values. These values are displayed in Table 6-12.

Table 6-12 Green House Gas Emission for Heavy Rail and Light Rail Transit Systems

	GHg per unit of travel (kg CO2E/pm)				
	HR		LR		% Difference
Max	The Greater Cleveland Regional Transit Authority	0.5403	The Greater Cleveland Regional Transit Authority	0.444	19.66%
Min	San Francisco Bay Area Rapid Transit District	0.0343	Central Puget Sound Regional Transit Authority	0.018	60.39%
Mean	0.161		0.144		11.04%
% Difference max and min	176.15%		184.10%		

These ranges have also been graphed and are shown in Figure 6-4.

Figure 6-4 CO2E/pkm Ranges for Heavy Rail and Light Rail Transit Systems



These tables and graphs show similar findings to the energy analysis – there is great disparity within modes as expected due to the same energy range between modes. There is a greater disparity between the minimum CO2E emissions than with energy between systems, however this can be accounted for due to the differing emission factors between states. Not all states will have the same emissions factors meaning some systems may have much different CO2E emissions despite having similar energy consumptions, or systems with slight disparity in energy consumption may have greater disparity in emissions . According to the US EPA, the average automobile emits 423 grams of CO2 per mile (Office of Transportation and Air Quality United States Environmental Protection Agency, 2011). When converted to units utilized in this study, the average emission value is 262 grams/km. Of the systems in this study, 29 of the 33 exceeded this level of environmental performance including 11 HR and 18 LR. These findings are in line with the literature review's hierarchy of modes, as well as past studies that find transit system performance to exceed private auto performance under the greenhouse gas criteria.

When comparing the highest performing systems of each mode, it is evident that Central Puget Sound Transit Authority (LR), offers better energy efficiency than San

Francisco Bay Area Rapid Transit District with a percent difference of 60.39. The least efficient systems of each type are both legs of the Greater Cleveland Regional Transit District and differ by 19.66%. On average, LR systems offer higher energy efficiency with a slight margin indicated by a percent difference of a 11.04%.

When comparing LR and HR systems for CO2 emissions, of the highest performing systems, 5 are LR, while only 3 are HR. The majority of the top 10 performers are LR which is in line with superior performance reflected in the range analysis in table 6-11. However, as all emissions estimates are based on energy consumption in this study, further commentary is not within the scope of this research. As discussed above, energy consumption is likely related to a host of factors related to the mode, the system configuration, and urban characteristics all of which will too impact emissions. Another factor to consider for further analysis is the impact of air quality policy on the emissions of different system. These are outside of the scope of this study and will need to be further expanded upon in future studies..

Factor 3 is composed of emissions for three common pollutants represented in the eGrid database: SO_2, NO_x and Hg. Table 6-13, Table 6-14, and Table 6-15 represent ranking and quartile performance ranges for SO_2, NO_x and Hg respectively.

Table 6-13 SO_2 Emissions Ranking for Heavy Rail and Light Rail Transit Systems

Rank	Operator	Mode	kg SO_2/pkm	Performance
1	Central Puget Sound Regional Transit Authority	LR	8.79E-06	Highest
2	San Francisco Bay Area Rapid Transit District	HR	2.47E-05	LR
3	Los Angeles County Metropolitan Transportation Authority	LR	2.51E-05	6
4	Valley Metro Rail, Inc.	LR	3.51E-05	HR
5	Los Angeles County Metropolitan Transportation Authority	HR	4.54E-05	2
6	Tri-County Metropolitan Transportation District of Oregon	LR	4.84E-05	
7	Sacramento Regional Transit District	LR	4.99E-05	
8	San Diego Metropolitan Transit System	LR	5.16E-05	
9	San Francisco Municipal Railway	LR	5.44E-05	High
10	MTA New York City Transit	HR	1.09E-04	LR
11	Denver Regional Transportation District	LR	1.60E-04	5
12	Dallas Area Rapid Transit	LR	2.12E-04	HR
13	Port Authority Trans-Hudson Corporation	HR	2.33E-04	4
14	Port Authority of Allegheny County	LR	2.37E-04	
15	Santa Clara Valley Transportation Authority	LR	2.51E-04	
16	Chicago Transit Authority	HR	2.72E-04	
17	MTA Staten Island Railway	HR	3.08E-04	
18	Metropolitan Transit Authority of Harris County, Texas	LR	3.30E-04	Low
19	Niagara Frontier Transportation Authority	LR	3.50E-04	LR
20	Massachusetts Bay Transportation Authority	LR	3.75E-04	5
21	Bi-State Development Agency	LR	4.15E-04	HR
22	Massachusetts Bay Transportation Authority	HR	4.57E-04	3
23	Utah Transit Authority	LR	4.69E-04	
24	Metropolitan Atlanta Rapid Transit Authority	HR	5.22E-04	
25	Miami-Dade Transit	HR	5.85E-04	

Rank	Operator	Mode	kg SO_2/pkm	Performance
26	The Greater Cleveland Regional Transit Authority	LR	7.06E-04	Poorest
27	Washington Metropolitan Area Transit Authority	HR	8.91E-04	LR
28	Southeastern Pennsylvania Transportation Authority	HR	1.00E-03	4
29	Charlotte Area Transit System	LR	2.22E-03	HR
30	Maryland Transit Administration	LR	2.60E-03	4
31	Maryland Transit Administration	HR	2.90E-03	
32	Metro Transit	LR	3.06E-03	
33	The Greater Cleveland Regional Transit Authority	HR	3.73E-03	
System Mean			7.27E-05	

Table 6-14 NOx Emissions Ranking for Heavy Rail and Light Rail Transit Systems

Rank	Operator	Mode	kg Nox/pkm	Performance
1	Central Puget Sound Regional Transit Authority	LR	2.15E-05	Highest
2	San Francisco Bay Area Rapid Transit District	HR	2.33E-05	LR
3	Los Angeles County Metropolitan Transportation Authority	LR	2.38E-05	5
4	Valley Metro Rail, Inc.	LR	3.32E-05	HR
5	Tri-County Metropolitan Transportation District of Oregon	LR	3.92E-05	3
6	MTA New York City Transit	HR	4.10E-05	
7	Los Angeles County Metropolitan Transportation Authority	HR	4.30E-05	
8	Sacramento Regional Transit District	LR	4.72E-05	
9	San Diego Metropolitan Transit System	LR	4.88E-05	High
10	San Francisco Municipal Railway	LR	5.15E-05	LR
11	Port Authority Trans-Hudson Corporation	HR	6.38E-05	5
12	Port Authority of Allegheny County	LR	6.50E-05	HR
13	Dallas Area Rapid Transit	LR	7.31E-05	4
14	Metropolitan Atlanta Rapid Transit Authority	HR	8.96E-05	
15	Massachusetts Bay Transportation	LR	1.01E-04	

Rank	Operator	Mode	kg Nox/pkm	Performance
	Authority			
16	Chicago Transit Authority	HR	1.15E-04	
17	MTA Staten Island Railway	HR	1.16E-04	
18	The Greater Cleveland Regional Transit Authority	LR	1.23E-04	Low
19	Massachusetts Bay Transportation Authority	HR	1.24E-04	LR
20	Niagara Frontier Transportation Authority	LR	1.32E-04	6
21	Bi-State Development Agency	LR	1.43E-04	HR
22	Utah Transit Authority	LR	1.89E-04	2
23	Southeastern Pennsylvania Transportation Authority	HR	1.92E-04	
24	Santa Clara Valley Transportation Authority	LR	2.55E-04	
25	Metropolitan Transit Authority of Harris County, Texas	LR	2.82E-04	
26	Miami-Dade Transit	HR	3.31E-04	Poorest
27	Washington Metropolitan Area Transit Authority	HR	3.80E-04	LR
28	Denver Regional Transportation District	LR	4.15E-04	4
29	Charlotte Area Transit System	LR	4.25E-04	HR
30	Maryland Transit Administration	LR	5.00E-04	4
31	Maryland Transit Administration	HR	5.55E-04	
32	Metro Transit	LR	7.65E-04	
33	The Greater Cleveland Regional Transit Authority	HR	9.32E-04	
	System Mean		1.08E-04	

Table 6-15 Hg Pollution Rankings for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	kg Hg /pkm	Performance
1	San Francisco Bay Area Rapid Transit District	HR	1.207E-10	Highest
2	Los Angeles County Metropolitan Transportation Authority	LR	1.228E-10	LR
3	Valley Metro Rail, Inc.	LR	1.715E-10	6
4	Los Angeles County Metropolitan Transportation Authority	HR	2.221E-10	HR
5	Sacramento Regional Transit District	LR	2.440E-10	2
6	San Diego Metropolitan Transit System	LR	2.524E-10	
7	San Francisco Municipal Railway	LR	2.664E-10	
8	Tri-County Metropolitan Transportation District of Oregon	LR	2.751E-10	
9	Central Puget Sound Regional Transit Authority	LR	4.648E-10	High
10	MTA New York City Transit	HR	5.790E-10	LR
11	Denver Regional Transportation District	LR	9.177E-10	5
12	Port Authority Trans-Hudson Corporation	HR	1.153E-09	HR
13	Port Authority of Allegheny County	LR	1.175E-09	3
14	Massachusetts Bay Transportation Authority	LR	1.489E-09	
15	Metropolitan Atlanta Rapid Transit Authority	HR	1.578E-09	
16	Santa Clara Valley Transportation Authority	LR	1.623E-09	
17	MTA Staten Island Railway	HR	1.639E-09	Low
18	Miami-Dade Transit	HR	1.704E-09	LR
19	Massachusetts Bay Transportation Authority	HR	1.815E-09	5
20	Niagara Frontier Transportation Authority	LR	1.866E-09	HR
21	Dallas Area Rapid Transit	LR	2.088E-09	3
22	Metropolitan Transit Authority of Harris County, Texas	LR	2.679E-09	
23	The Greater Cleveland Regional Transit Authority	LR	3.158E-09	
24	Utah Transit Authority	LR	3.390E-09	
25	Chicago Transit Authority	HR	4.000E-09	Poorest
26	Bi-State Development Agency	LR	4.085E-09	LR
27	Southeastern Pennsylvania Transportation Authority	HR	5.197E-09	4
28	Charlotte Area Transit System	LR	7.157E-09	HR

Rank	Operator Name	Mode	kg Hg /pkm	Performance
29	Maryland Transit Administration	HR	9.343E-09	4
30	Metro Transit	LR	1.176E-08	
31	Maryland Transit Administration	LR	1.350E-08	
32	The Greater Cleveland Regional Transit Authority	HR	1.433E-08	
33	Washington Metropolitan Area Transit Authority	HR		Removed from this factor.
System Mean			1.054E-09	

The ranges for SO_2, NO_x and Hg are presented in Table 6-16.

Table 6-16 Pollutant Emission Ranges for Heavy Rail and Light Rail Transit Systems

	Pollutant	kg SO2/pkm	km Nox/pkm	kg Hg /pkm
HR (HR)	Max	3.728E-03	9.315E-04	1.433E-08
	Min	2.466E-05	2.335E-05	1.207E-10
	% Difference	197.3713%	190.2192%	196.6585%
	Mean	8.5191E-04	2.3115E-04	3.4729E-09
LR (LR)	Max	3.061E-03	7.648E-04	1.350E-08
	Min	8.795E-06	2.145E-05	1.228E-10
	% Difference	198.8539%	189.0852%	196.3942%
	Mean	5.7488E-04	1.8885E-04	2.8286E-09
%Difference Modes	Max	19.66%	19.66%	5.91%
	Min	94.85%	8.46%	-1.77%
	Mean	38.83%	20.14%	20.45%

Similar to the CO2E, these emission ranges are based on the ranges in energy consumption as well as the emission factors and show greater disparity between maximum and minimum within modes than energy does. The disparity within and across system sets compared to energy can be associated with the variation in factors across grids. For Hg and SO_2, 6 of the highest performing systems are LR, for NO_x 5 of the top performers are LR. These results are a combination of energy efficiency and grid efficiency. For SO_2 the minimum (high performance) system, LR achieves superior performance with a percent difference of 94.85%, while for the maximum(low performance) LR also attains greater performance with 19.66% difference, while for the mean LR achieves greater performance at a percent difference of 38.83%. For NO_X,in both the highest and least performing systems, LR achieves greater performance with differences of 19.66% and 8.46% respectively, while on average LR achieves greater results with a difference of 20.14%. In Hg pollution, or the highest performing systems, LR system outperforms HR at 5.91%, however the lowest performing HR outperforms the lowest performing LR by 1.77%. Based on average performance LR offers lower emissions per pkm with a difference of 20.45%.

To conclude, the environmental factors considered in this study represent a host of environmental impacts of travel – energy consumption, global climate change impacts, and environmental pollutants. Based on the systems analyzed through trend line analysis, LR systems on average may provide greater energy efficiency per passenger km travelled, however it is unknown whether or not this trend continues into higher levels of system capacity as LR systems are typically planned for lower capacities than HR systems and there are no LR systems that provide higher capacities within the dataset. Between both system sets there is little disparity between the maximum, minimum, and average values, indicating similar levels of performance overall.

29 out of 33 systems included in the study exceed environmental performance of a single occupancy automobile based on EPA figures for greenhouse gas emissions indicating that transit is a sustainable mode in line with the literature review. Within the second and third environmental factors, the slight disparities observed in the first

factor, energy, expanded greatly. These differences are not due to system type, but due to factors exogenous to system design – the grids from which systems purchase power.

It is essential to note that energy consumption influences the second and third factors greatly in this research and that outside of system mode, other factors such as system layout and operational variables such as running speed and acceleration time have great influence on energy consumption and these factors must be further researched in future studies to better outline the sustainability performance of these systems.

Overall conclusions based on direct numerical comparison are summarized in the following Table 6-17:

Table 6-17 Summary of Analysis of Environmental Factors

	Highest Performance Systems	Lowest Performance Systems	Mean	Trend
Energy	High end HR systems achieve better performance than LR systems, LR systems are better represented.	LR attains greater performance than HR.	Null hypothesis (difference between means is statistically significant) rejected at 95%.	LR trend line indicates higher efficiency.
CO2E	LR systems are better represented.	LR attains slightly greater performance than HR.	LR attains greater performance.	N/A
SO2	LR systems are better represented.	LR attains slightly greater performance than HR.	LR attains much greater performance.	N/A
NOx	LR systems are better represented.	LR attains slightly greater performance than HR.	LR attains greater performance.	N/A
Hg	LR systems are better represented.	LR achieves better performance than HR systems.	LR attains greater performance.	N/A

From the numerical analysis, these preliminary results indicate overall better environmental performance for LR systems when compared to HR systems. The first factor, energy consumption shows balanced performance for HR with a distribution across the four performance quartiles from high to low of 3,3,4,3 and for LR or 5,5,5,5. While the top three systems are HR, the majority of top tier systems are LR indicating better performance in general for LR. For CO2E the performance breakdowns are 4,3,3,3, for HR and 4,6, 5, 5 for LR. LR is better represented in the upper tiers, indicating better overall performance. However, this indicator has balanced performance for both system sets. For SO_x the performance breakdowns are 2,4,3,4 for HR and 6,5,5,4 for LR, indicating LR has better performance than HR. For NO_x the performance breakdowns are 3,4,2,4 for HR and 5,5,6,4 for LR, indicating balanced performance for LR, but overall better performance for LR. For Hg the performance breakdowns are 2,3,5,3 for HR and 6,5,5,4 for HR, indicating better performance for LR. Despite being directly related to energy consumption and factors not in the control of the system itself, emissions are still counted as they are related to the system's sustainable mobility and inasmuch they are included in the comprehensive sustainable mobility analysis presented in this thesis for system comparison. However, in the context of modal comparison, emission performance analysis should be taken in the context of grid and energy consumption.

While LR systems attain in general better performance by measure of representation in higher tier performance categories, both system sets have high and low performance systems. There is a spectrum of environmental performance across all factors given the complexity of the grids involved and the complexity involved in energy consumption.

6.5.2 Economic Factors

The first four economic factors, operating cost per passenger km, average fare per trip, average travel time, and cost recovery were calculated using data directly from the NTD and required no additional expansion or treatment. The final factor, transit economy interactions required the use of gross domestic product for the urban area served by the transit system. GDP values were obtained using data provided by the Bureau of Economic Analysis from the U.S. Department of Commerce (Bureau of Economic Analysis, 2011). For this study the GDP value of the host city of the transit agency, as stated within the NTD was utilized. For systems that serve a broader area, such as MTA New York or Port Authority Trans-Hudson Corporation, the GDP of the metropolitan statistical area was utilized.

Only factor one is normalized per passenger kilometre travelled, while factor two utilizes pkm in its calculation and is based on an average. Factor three is an average based on trips and factor four is a percentage calculated for each system, while factor five is based on pkm and GDP. All factors are shown in Table 6-18.

Table 6-18 Economic Factors for Heavy Rail and Light Rail Transit Systems

	Operator Name	City	op cost/pkm	Average travel time costs(minutes)	Average Fare $ (USD)	Recovery (%)	PKM/GDP
HR	Massachusetts Bay Transportation Authority	Boston	$0.39	12.084	1.102	49.98%	2.729E-09
HR	MTA New York City Transit	New York	$0.21	13.111	0.983	71.68%	1.361E-08
HR	Port Authority Trans-Hudson Corporation	Jersey City	$0.53	13.769	1.261	35.14%	4.929E-10
HR	MTA Staten Island Railway	New York	$0.49	16.696	0.854	18.30%	6.320E-11
HR	Southeastern Pennsylvania Transportation Authority	Philadelphia	$0.24	13.637	0.892	51.12%	2.184E-09
HR	Washington Metropolitan Area Transit Authority	Washington	$0.30	13.592	1.698	61.96%	6.873E-09
HR	Maryland Transit Administration	Baltimore	$0.58	10.480	0.858	21.42%	7.117E-10
HR	Metropolitan Atlanta Rapid Transit Authority	Atlanta	$0.22	14.431	0.756	34.27%	3.213E-09
HR	Miami-Dade Transit	Miami	$0.37	15.572	1.026	23.40%	8.853E-10
HR	The Greater Cleveland Regional Transit Authority	Cleveland	$0.54	20.738	1.112	18.03%	4.419E-10
HR	Chicago Transit Authority	Chicago	$0.22	19.875	1.135	53.07%	4.379E-09
HR	San Francisco Bay Area Rapid Transit District	San Francisco-Oakland-Fremont	$0.21	21.695	3.060	71.56%	7.575E-09
HR	Los Angeles County Metropolitan Transportation Authority	Los Angeles	$0.24	13.174	0.730	38.73%	5.568E-10
LR	Tri-County Metropolitan Transportation District of Oregon	Portland	$0.32	21.375	0.869	34.70%	2.761E-09
LR	Central Puget Sound Regional Transit Authority	Seattle	$0.46	22.961	1.227	23.22%	4.323E-10

Operator Name	City	op cost/pkm	Average travel time costs(minutes)	Average Fare $ (USD)	Recovery (%)	PKM/GDP
Massachusetts Bay Transportation Authority	Boston	$0.56	15.145	1.064	49.47%	8.778E-10
Niagara Frontier Transportation Authority	Buffalo	$0.90	14.415	0.723	19.08%	6.539E-10
Port Authority of Allegheny County	Pittsburgh	$0.93	21.694	1.130	15.79%	5.246E-10
Maryland Transit Administration	Baltimore	$0.45	20.829	0.869	17.80%	6.774E-10
Charlotte Area Transit System	Charlotte	$0.58	17.422	0.988	20.02%	2.665E-10
The Greater Cleveland Regional Transit Authority	Cleveland	$0.58	22.565	1.112	20.36%	2.323E-10
Metro Transit	Minneapolis	$0.29	21.195	0.991	40.26%	4.930E-10
Metropolitan Transit Authority of Harris County, Texas	Houston	$0.38	11.559	0.545	39.06%	1.101E-10
Dallas Area Rapid Transit	Dallas	$0.55	24.087	0.794	12.62%	5.813E-10
Bi-State Development Agency	St. Louis	$0.24	20.830	1.075	31.55%	1.905E-09
Utah Transit Authority	Salt Lake City	$0.30	17.845	0.777	37.18%	1.531E-09
Denver Regional Transportation District	Denver	$0.32	22.803	1.107	31.12%	1.548E-09
Santa Clara Valley Transportation Authority	San Jose	$0.70	19.878	0.883	15.19%	4.799E-10
San Francisco Municipal Railway	San Francisco	$0.80	17.797	0.771	22.51%	7.154E-10
Sacramento Regional Transit District	Sacramento	$0.36	16.446	0.943	30.21%	1.593E-09
San Diego Metropolitan Transit System	San Diego	$0.20	20.441	1.085	54.26%	1.933E-09
Los Angeles County Metropolitan Transportation Authority	Los Angeles	$0.31	18.914	0.662	18.30%	8.002E-10
Valley Metro Rail, Inc.	Phoenix	$0.23	29.920	0.764	28.08%	8.137E-10

Factor 1, operating costs/pkm, values have been ranked for both system types and ranked by quartile performance ranges. These values are shown in Table 6-19.

Table 6-19 Operating Costs/pkm for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	op cost/pkm	Performance
1	San Diego Metropolitan Transit System	LR	$0.203	Highest
2	San Francisco Bay Area Rapid Transit District	HR	$0.207	LR
3	MTA New York City Transit	HR	$0.214	2
4	Metropolitan Atlanta Rapid Transit Authority	HR	$0.216	HR
5	Chicago Transit Authority	HR	$0.216	6
6	Valley Metro Rail, Inc.	LR	$0.234	
7	Los Angeles County Metropolitan Transportation Authority	HR	$0.242	
8	Southeastern Pennsylvania Transportation Authority	HR	$0.244	
9	Bi-State Development Agency	LR	$0.245	High
10	Metro Transit	LR	$0.289	LR
11	Washington Metropolitan Area Transit Authority	HR	$0.299	7
12	Utah Transit Authority	LR	$0.304	HR
13	Los Angeles County Metropolitan Transportation Authority	LR	$0.313	2
14	Tri-County Metropolitan Transportation District of Oregon	LR	$0.317	
15	Denver Regional Transportation District	LR	$0.318	
16	Sacramento Regional Transit District	LR	$0.360	
17	Miami-Dade Transit	HR	$0.369	
18	Metropolitan Transit Authority of Harris County, Texas	LR	$0.381	Low
19	Massachusetts Bay Transportation Authority	HR	$0.395	LR
20	Maryland Transit Administration	LR	$0.449	5
21	Central Puget Sound Regional Transit Authority	LR	$0.456	HR
22	MTA Staten Island Railway	HR	$0.491	4
23	Port Authority Trans-Hudson Corporation	HR	$0.526	

Rank	Operator Name	Mode	op cost/pkm	Performance
24	The Greater Cleveland Regional Transit Authority	HR	$0.541	
25	Dallas Area Rapid Transit	LR	$0.555	
26	Massachusetts Bay Transportation Authority	LR	$0.564	
27	The Greater Cleveland Regional Transit Authority	LR	$0.577	Poorest
28	Maryland Transit Administration	HR	$0.581	LR
29	Charlotte Area Transit System	LR	$0.582	6
30	Santa Clara Valley Transportation Authority	LR	$0.704	HR
31	San Francisco Municipal Railway	LR	$0.800	1
32	Niagara Frontier Transportation Authority	LR	$0.899	
33	Port Authority of Allegheny County	LR	$0.927	
	System Mean		$0.425	

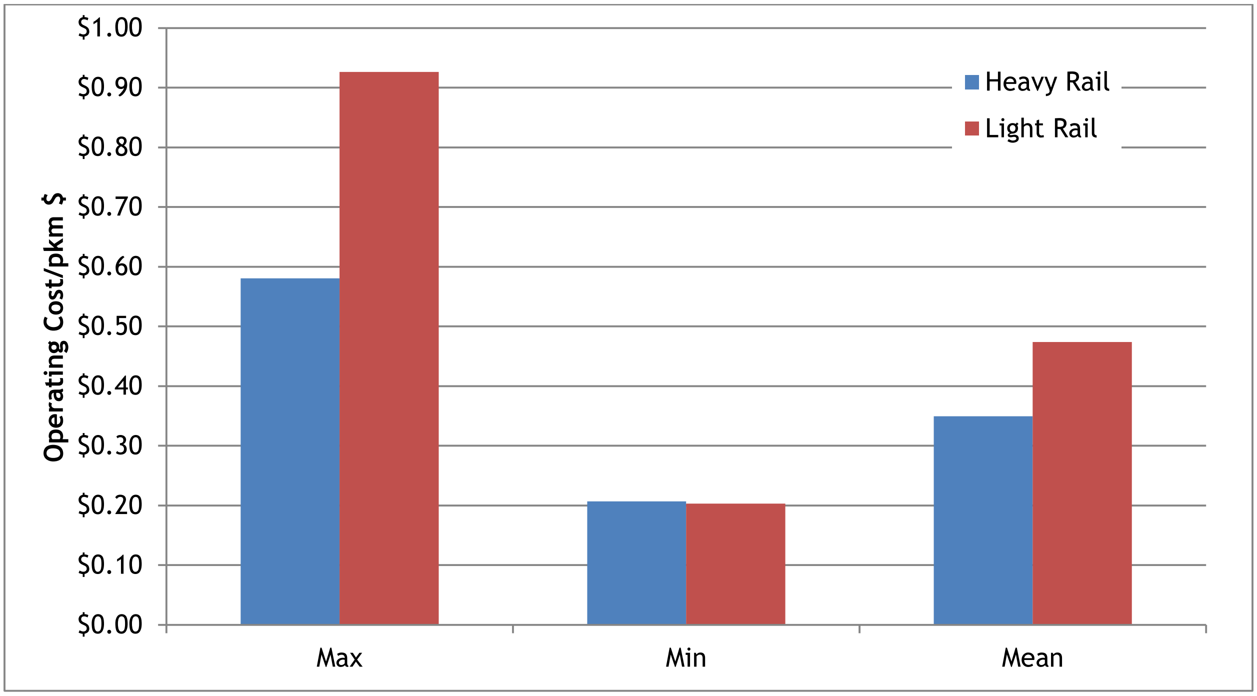
The maximum, minimum, and average values for each system set, as well as the percent differences between and within system sets have also been determined. These values are displayed in Table 6-20.

Table 6-20 Operating Cost/pkm ranges for Heavy Rail and Light Rail Transit Systems

	Operating cost pkm				
	HR		LR		% Difference
Maximum	Maryland Transit Administration	$0.581	Port Authority of Allegheny County	$0.927	45.870%
Minimum	San Francisco Bay Area Rapid Transit District	$0.207	San Diego Metropolitan Transit System	$0.203	1.921%
Mean	$0.349		$0.474		30.244%
% Difference Max and Min	94.95%		128.13%		

These ranges are graphed in Figure 6-5 Operating cost/pkm ranges for Heavy Rail and Light Rail Transit Systems.

Figure 6-5 Operating cost/pkm ranges for Heavy Rail and Light Rail Transit Systems



As demonstrated through the tables and figure, there is a disparity between operating costs and system for both mean and maximum operating costs/pkm. While for the minimal values, which represent highly efficient systems, there is little difference at 1.921%, the maximum values have a difference of 45.870% indicating a great difference in operating cost efficiency between the least efficient systems in both systems classes. On average, HR systems offer better efficiency for operating costs, with the percent difference between system types being 30.244%.

Within system sets, there is great disparity between the highest performer and least performer. For HR, the strongest performing system, San Francisco Bay Area Rapid Transit District and the least efficient system, Maryland Transit Administration had a percent difference of 94.95%, while in the LR category San Diego Metropolitan Transit Authority and Port Authority Allegheny County differed by 128.13%. Of the highest performing systems, 6 are HR, with the majority of HR systems fitting into the top two performance categories. In general, HR offer better cost performance overall compared to LR systems based on ranking and range performance.

To further explore system cost performance, two graphs have been generated. Figure 6-6 uses a log scale graph to show all systems on one figure, while

Figure 6-7 shows 33 systems, excluding MTA New York to show the 33 systems on a regular scale graph.

Figure 6-6 Log Scale Passenger Kilometres Travelled and Operating Costs for Propulsion for Heavy Rail and Light Rail Transit Systems

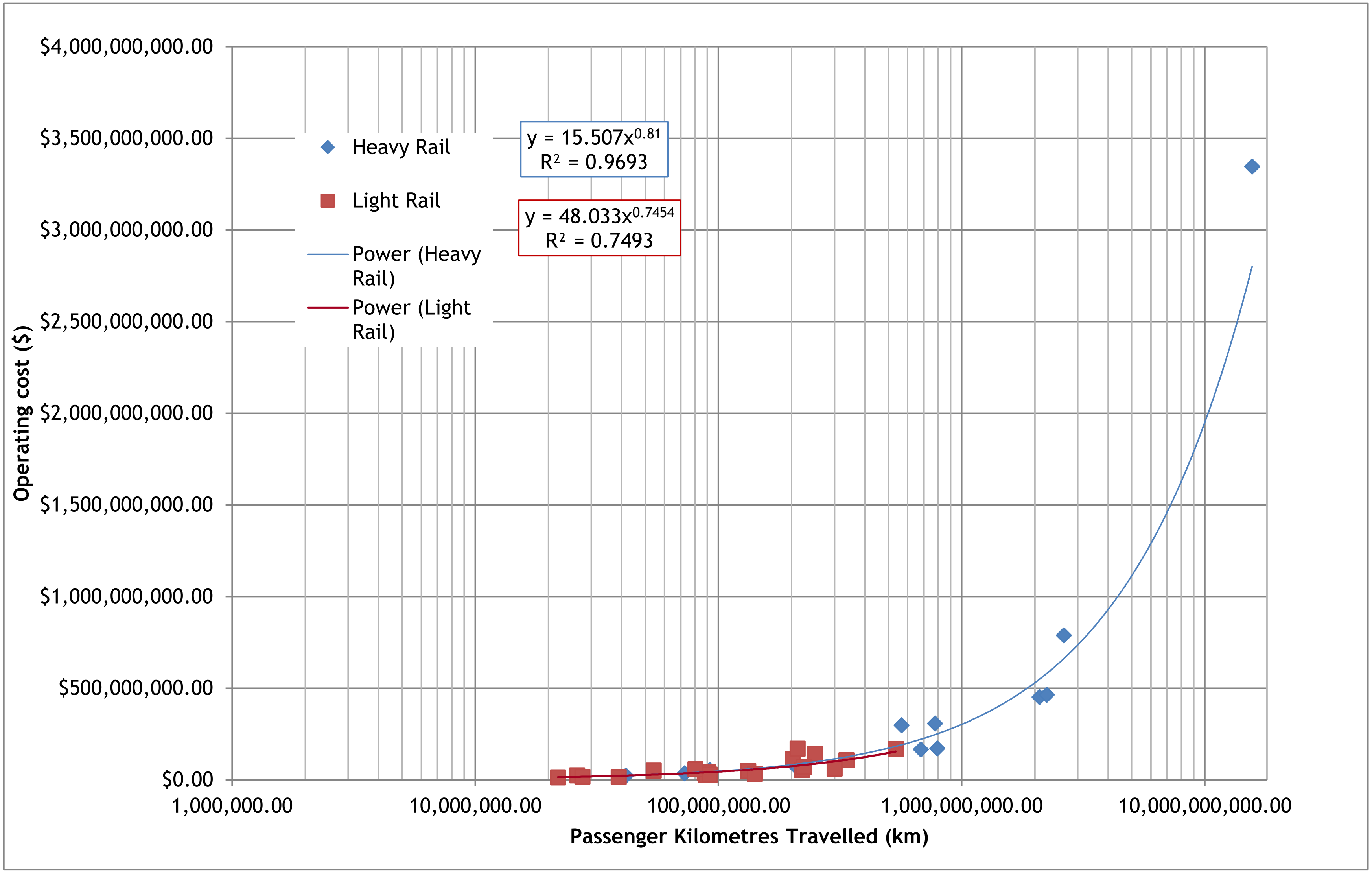
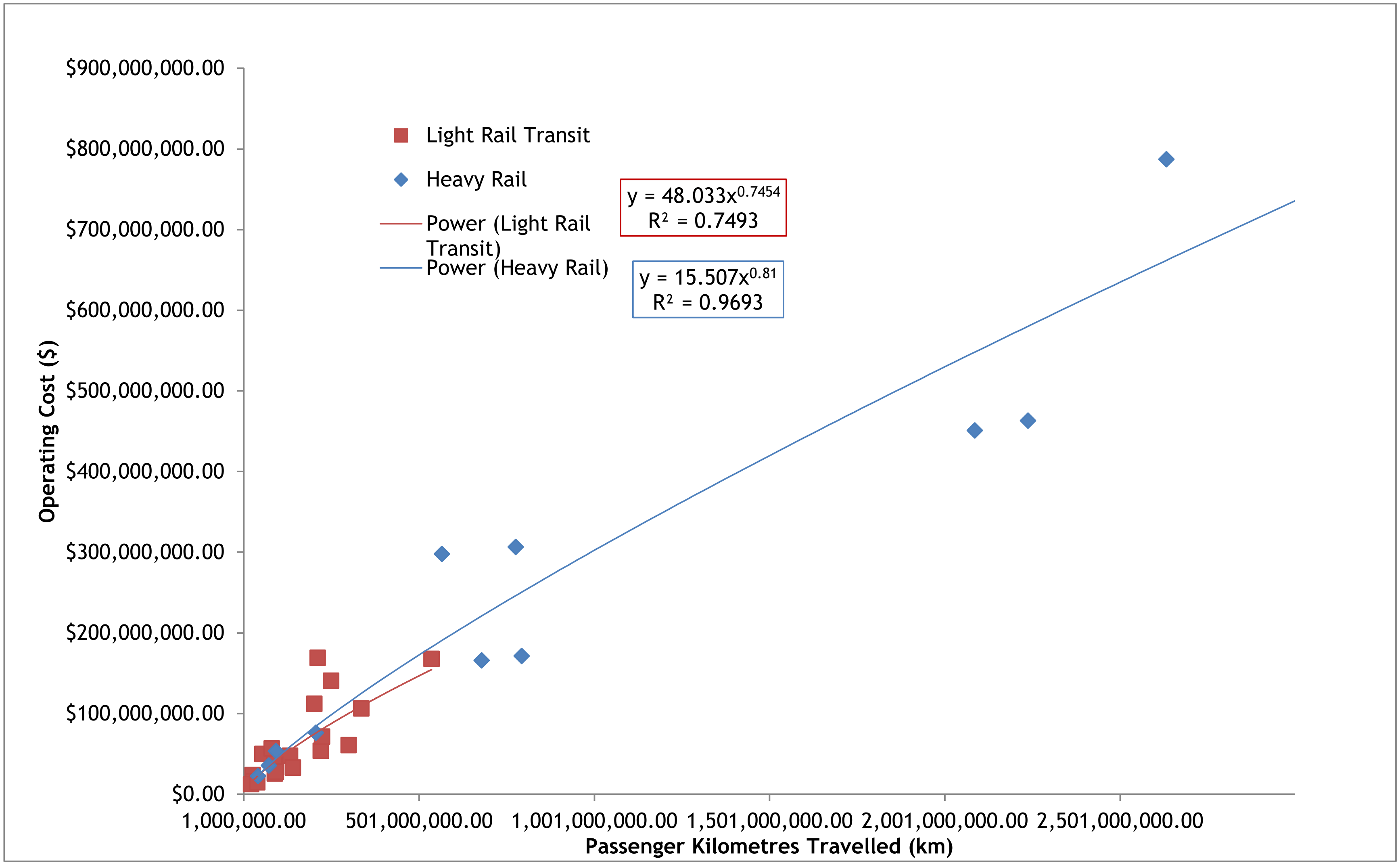


Figure 6-7 Passenger Kilometres Travelled and Operating Cost for Propulsion for HR and LR Transit Systems



As noted in the figures, the trend is for LR systems to present lower operating costs per passenger km travelled than HR systems. Both trend lines present high r square values indicating a high level of fit. This result is in contrast to the high performance and average operating cost/pkm findings for the range analysis above. This may be due to the strong performance of high performance systems in the LR category influencing the trend line. Similar to the energy discussion, no data points exist for high pkm LR systems so it is important to note that this trend line may not be extrapolated to higher capacity systems. As operating costs are determined by maintenance, labour, and other fees paid by the operator to provide transit service that are outside of the scope of this study, further research can supplement this rudimentary analysis.

It is important to note that factors that influence operating costs, such as labour costs, material costs, and cost of fuel/energy may be influenced by regional or local factors which are not analyzed within this study. While there is a trend showing lower operating costs, in general, for LR systems on the graphs, there are other factors that need to be included in future studies that take into account local impacts on operating costs that go beyond mode choice.

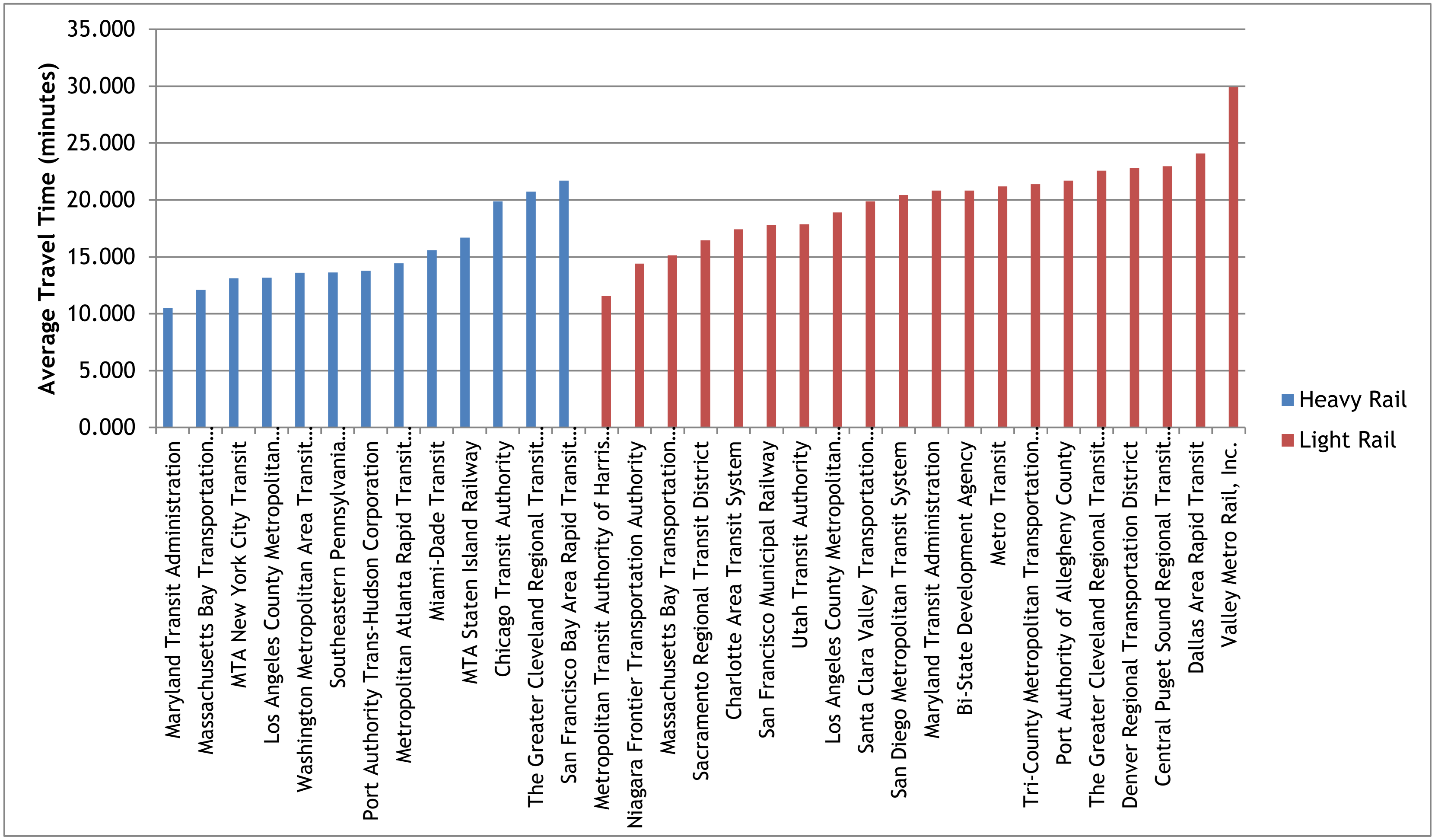
The second factor, average travel time, which represents the time cost incurred per trip on average by system users is displayed from least travel time to most travel time and ranked by performance level for each system in Table 6-21. These values are also graphed in Figure 6-8 indicating the full range of values for average travel time across both system sets.

Table 6-21 Average Travel Time Costs for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	Average travel time costs(minutes)	Performance
1	Maryland Transit Administration	HR	10.48	Highest
2	Metropolitan Transit Authority of Harris County, Texas	LR	11.56	LR
3	Massachusetts Bay Transportation Authority	HR	12.08	1
4	MTA New York City Transit	HR	13.11	HR
5	Los Angeles County Metropolitan Transportation Authority	HR	13.17	7
6	Washington Metropolitan Area Transit Authority	HR	13.59	
7	Southeastern Pennsylvania Transportation Authority	HR	13.64	
8	Port Authority Trans-Hudson Corporation	HR	13.77	
9	Niagara Frontier Transportation Authority	LR	14.42	High
10	Metropolitan Atlanta Rapid Transit Authority	HR	14.43	LR
11	Massachusetts Bay Transportation Authority	LR	15.14	6
12	Miami-Dade Transit	HR	15.57	HR
13	Sacramento Regional Transit District	LR	16.45	3
14	MTA Staten Island Railway	HR	16.70	
15	Charlotte Area Transit System	LR	17.42	
16	San Francisco Municipal Railway	LR	17.80	
17	Utah Transit Authority	LR	17.85	
18	Los Angeles County Metropolitan Transportation Authority	LR	18.91	Low
19	Chicago Transit Authority	HR	19.88	LR
20	Santa Clara Valley Transportation Authority	LR	19.88	7
21	San Diego Metropolitan Transit System	LR	20.44	HR
22	The Greater Cleveland Regional Transit Authority	HR	20.74	2
23	Maryland Transit Administration	LR	20.83	
24	Bi-State Development Agency	LR	20.83	

Rank	Operator Name	Mode	Average travel time costs(minutes)	Performance
25	Metro Transit	LR	21.19	
26	Tri-County Metropolitan Transportation District of Oregon	LR	21.37	
27	Port Authority of Allegheny County	LR	21.69	Poorest
28	San Francisco Bay Area Rapid Transit District	HR	21.69	LR
29	The Greater Cleveland Regional Transit Authority	LR	22.57	6
30	Denver Regional Transportation District	LR	22.80	HR
31	Central Puget Sound Regional Transit Authority	LR	22.96	1
32	Dallas Area Rapid Transit	LR	24.09	
33	Valley Metro Rail, Inc.	LR	29.92	
System Mean			18.09	

Figure 6-8 Average Travel Time for Heavy and Light Rail Transit Systems



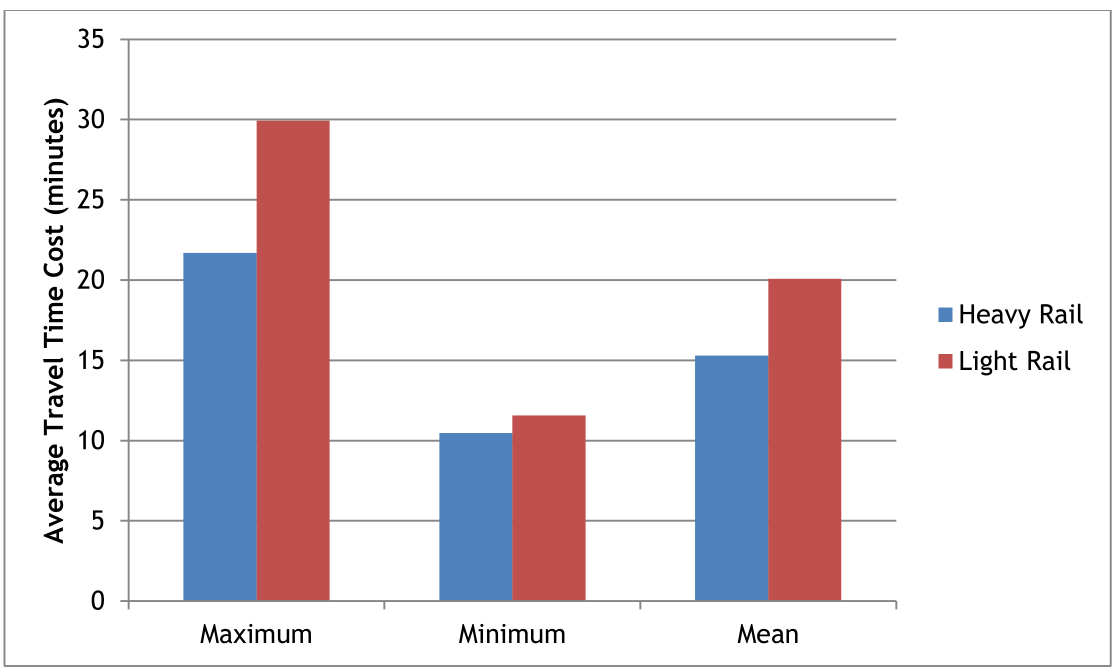
Maximum, minimum, and average values, along with percent differences between and within system sets have been calculated. These values are displayed in Table 6-22.

Table 6-22 Travel Time Cost Ranges for Heavy Rail and Light Rail Transit Systems

	Average Travel Time Cost (minutes)				
	HR		LR		% Difference
Maximum	San Francisco Bay Area Rapid Transit District	21.695	Valley Metro Rail, Inc.	29.92	31.87%
Minimum	Maryland Transit Administration	10.480	Metropolitan Transit Authority of Harris County, Texas	11.559	9.79%
Mean	15.296		19.906		-26.19%
% Difference Max and Min	69.71%		88.53%		

This data is graphed in Figure 6-9.

Figure 6-9 Average Travel Time Costs for Heavy Rail and Light Rail Transit Systems



From the tables and figure, it can be seen that in general HR systems offer higher performance for average travel time than LR systems. When comparing maximum, minimum, and mean, the HR systems provide superior performance in all categories. For maximum travel time, the HR system, San Francisco Bay Area Rapid Transit District, outperforms Valley Metro Inc. with a percent difference of 31.87%. In the higher performance system category, Maryland Transit Administration outperforms Metropolitan Transit Authority of Harris County, Texas with a percent difference of 9.789%. The average performance of each system set has HR again outperforming LR, with a percent difference of 26.19%. Of the top performers, only 1 is a LR system, while the remaining systems to offer the least user costs for travel time are HR systems.

While a variety of planning factors, such as activity, residential, and employment centres served as well as size of system influence the travel time of the system, as well as operation factors such as system configuration and headway, these findings do indicate that NTD HR systems offer in general better travel time cost performance for users than LR systems.

Recalling the methodology and literature review, fare is determined by operators and reflects a number of decisions related to operations, finances, and policy. This factor represents the average price paid per revenue trip by customers and represents economic sustainability from the perspective of the end user. To investigate if trends exist in the NTD data set between HR and LR systems, the values for each system have been ranked and sorted into performance categories Table 6-23.

Table 6-23 Average User Fare Cost for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	Average User Fare Cost ($ USD)	Performance
1	Metropolitan Transit Authority of Harris County, Texas	LR	$0.55	Highest
2	Los Angeles County Metropolitan Transportation Authority	LR	$0.66	LR
3	Niagara Frontier Transportation Authority	LR	$0.72	6
4	Los Angeles County Metropolitan Transportation Authority	HR	$0.73	HR
5	Metropolitan Atlanta Rapid Transit Authority	HR	$0.76	2
6	Valley Metro Rail, Inc.	LR	$0.76	
7	San Francisco Municipal Railway	LR	$0.77	
8	Utah Transit Authority	LR	$0.78	
9	Dallas Area Rapid Transit	LR	$0.79	High
10	MTA Staten Island Railway	HR	$0.85	LR
11	Maryland Transit Administration	HR	$0.86	5
12	Maryland Transit Administration	LR	$0.87	HR
13	Tri-County Metropolitan Transportation District of Oregon	LR	$0.87	4
14	Santa Clara Valley Transportation Authority	LR	$0.88	
15	Southeastern Pennsylvania Transportation Authority	HR	$0.89	
16	Sacramento Regional Transit District	LR	$0.94	
17	MTA New York City Transit	HR	$0.98	
18	Charlotte Area Transit System	LR	$0.99	Low
19	Metro Transit	LR	$0.99	LR
20	Miami-Dade Transit	HR	$1.03	7
21	Massachusetts Bay Transportation Authority	LR	$1.06	HR
22	Bi-State Development Agency	LR	$1.08	2
23	San Diego Metropolitan Transit System	LR	$1.08	
24	Massachusetts Bay Transportation Authority	HR	1.10	
25	Denver Regional Transportation District	LR	$1.11	
26	The Greater Cleveland Regional Transit Authority	LR	$1.11	

Rank	Operator Name	Mode	Average User Fare Cost ($ USD)	Performance
27	The Greater Cleveland Regional Transit Authority	HR	$1.11	Poorest
28	Port Authority of Allegheny County	LR	$1.13	LR
29	Chicago Transit Authority	HR	$1.14	2
30	Central Puget Sound Regional Transit Authority	LR	$1.23	HR
31	Port Authority Trans-Hudson Corporation	HR	$1.26	5
32	Washington Metropolitan Area Transit Authority	HR	$1.70	
33	San Francisco Bay Area Rapid Transit District	HR	$3.06	
System Mean			$1.03	

These values are represented in Figure 6-10.

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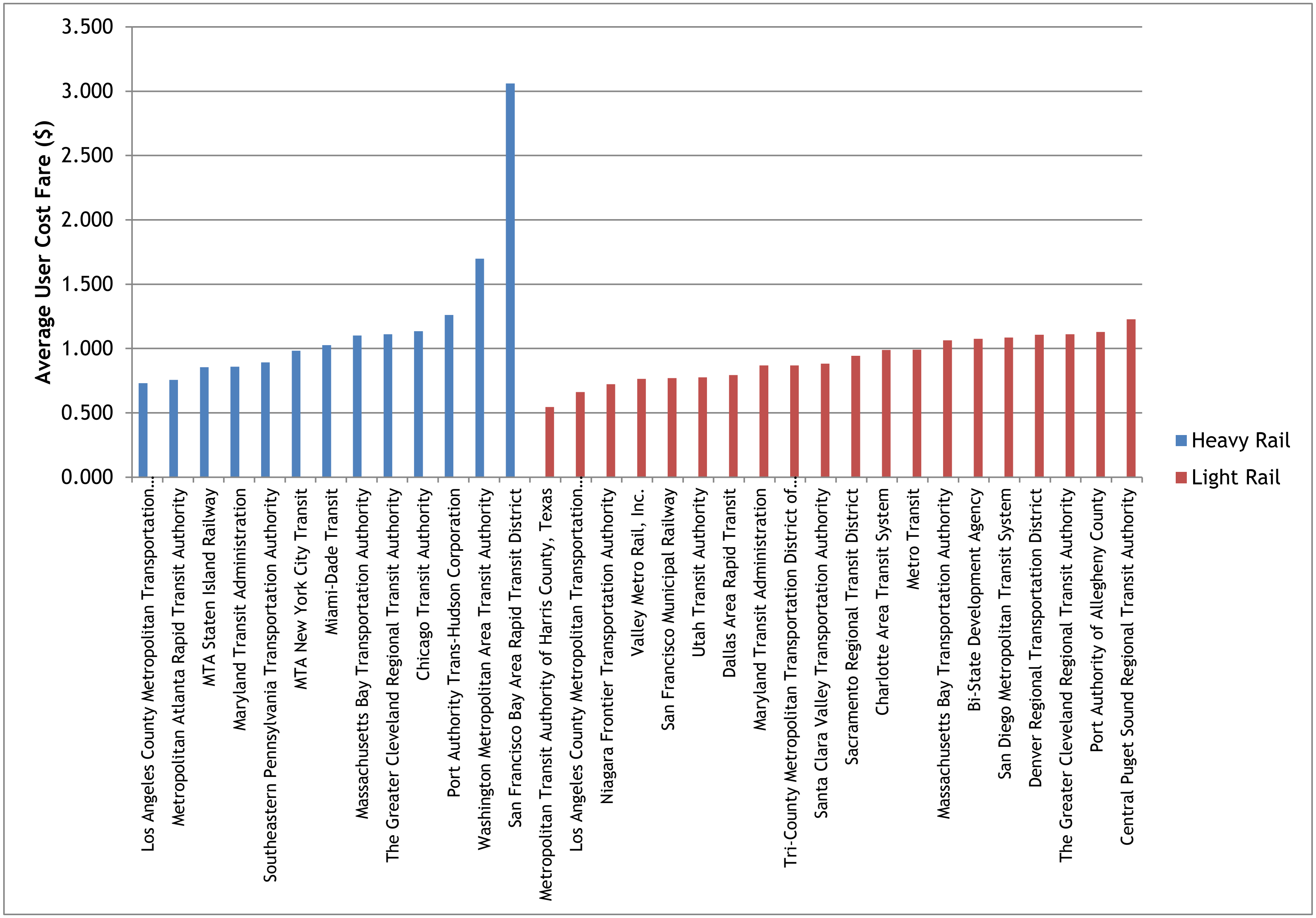
Figure 6-10 Average User Fare Costs for Heavy Rail and Light Rail Transit Systems



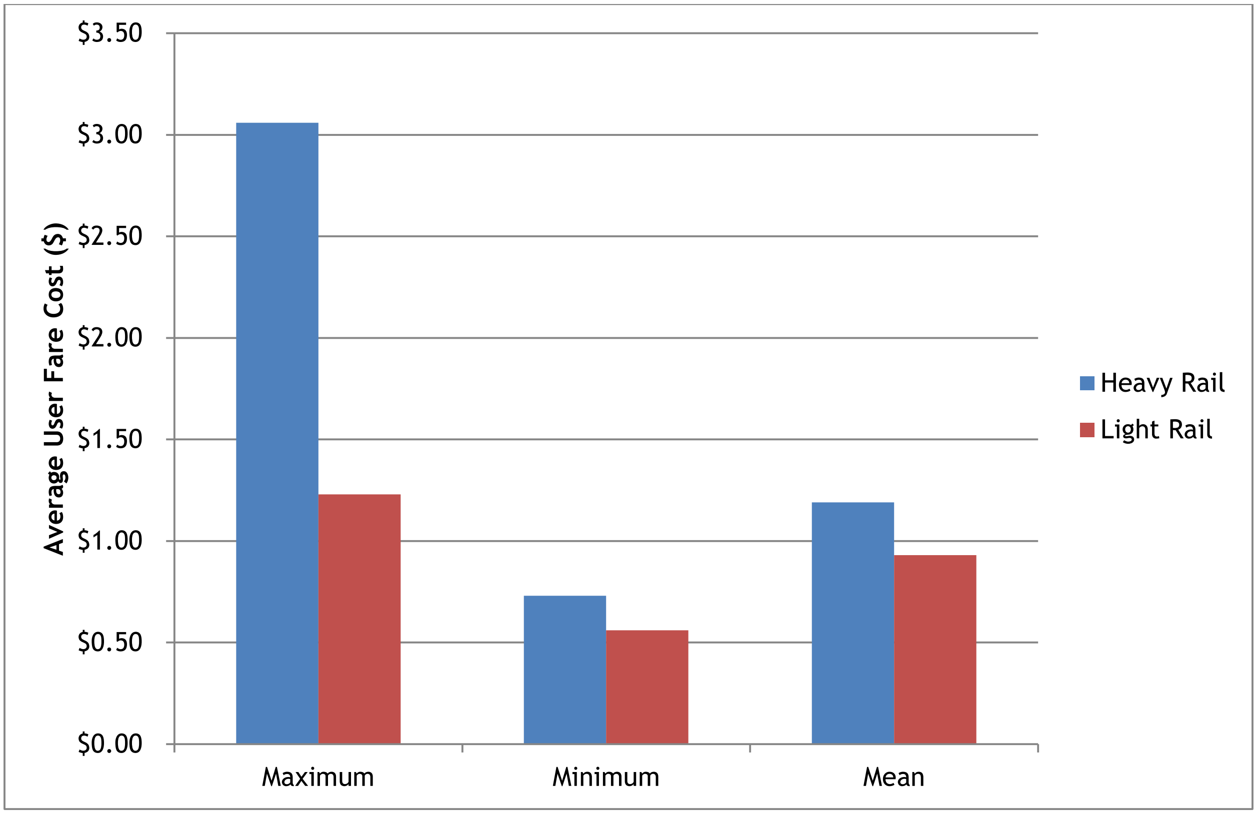
The maximum, minimum, and average values for each mode, as well as percent differences within and between system modes are presented in Table 6-24

Table 6-24 Average User Fare Cost Ranges for Heavy Rail and Light Rail Transit Systems

	Average User Fare Cost ($)				
	HR		LR		% Difference
Maximum	San Francisco Bay Area Rapid Transit District	$3.06	Central Puget Sound Regional Transit Authority	$1.23	85.515%
Minimum	Los Angeles County Metropolitan Transportation Authority	$0.73	Metropolitan Transit Authority of Harris County, Texas	$0.56	29.028%
Mean	$1.19		$0.92		25.70%
% Difference Max and Min	122.93%		74.86%		

This data is graphed in Figure 6-11.

Figure 6-11 Average User Fare Cost Ranges for Heavy Rail and Light Rail Transit Systems



As demonstrated in the tables and figure, in general LR systems have lower user costs for fare as represented by a much lower maximum with a 85.515% difference between low user benefit systems Central Puget Sound Transit Authority and San Francisco Bay Area Rapid Transit District, a difference of 29.028% between higher user benefit systems Metropolitan Transit Authority of Harris County and LA County Metropolitan Transportation Authority, and a difference between the means of 25.007%. Of the highest performing systems, only two are HR systems, with the majority of systems placed in the high and lowest performing categories. LR systems are almost evenly distributed throughout all four categories..

These factors are included to complete the benchmarking exercise and system comparison, and while in general LR systems offer lower costs to users, it cannot be established what the key factors that determine these lower costs are. It must be noted that, due to the policy driven nature of fare determination, a direct system to system comparison must be complemented with further research into other factors and hence no trends can be firmly established with this data.

The fourth factor represents the recovery of operating costs from user fees. The systems have been ranked and sorted by recovery % in Table 6-25.

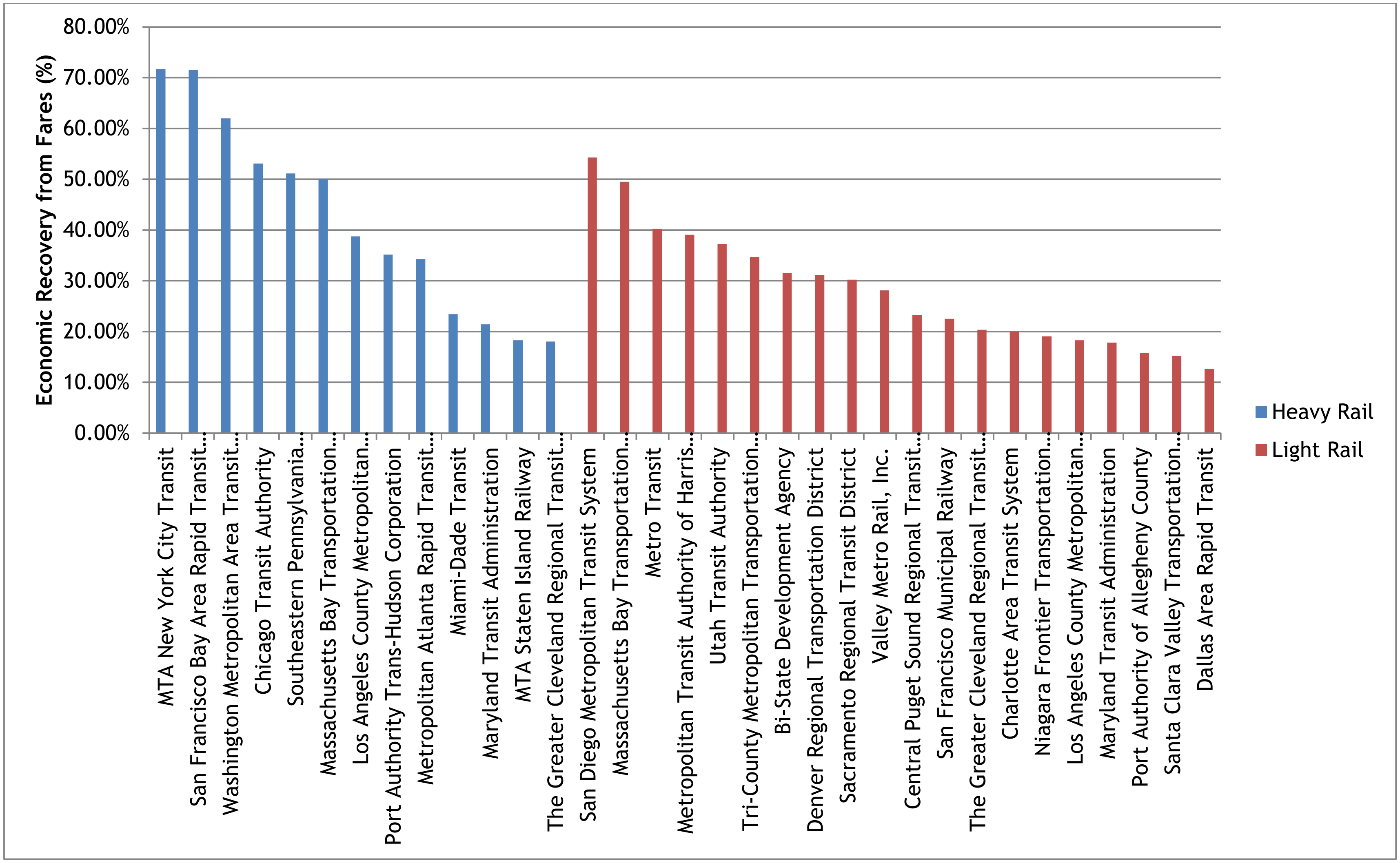
Table 6-25 Fare Recovery of Operating cost for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	Recovery (%)	Performance
1	MTA New York City Transit	HR	71.68%	Highest
2	San Francisco Bay Area Rapid Transit District	HR	71.56%	LR
3	Washington Metropolitan Area Transit Authority	HR	61.96%	2
4	San Diego Metropolitan Transit System	LR	54.26%	HR
5	Chicago Transit Authority	HR	53.07%	6
6	Southeastern Pennsylvania Transportation Authority	HR	51.12%	
7	Massachusetts Bay Transportation Authority	HR	49.98%	
8	Massachusetts Bay Transportation Authority	LR	49.47%	
9	Metro Transit	LR	40.26%	High
10	Metropolitan Transit Authority of Harris County, Texas	LR	39.06%	LR
11	Los Angeles County Metropolitan Transportation Authority	HR	38.73%	6
12	Utah Transit Authority	LR	37.18%	HR
13	Port Authority Trans-Hudson Corporation	HR	35.14%	3
14	Tri-County Metropolitan Transportation District of Oregon	LR	34.70%	
15	Metropolitan Atlanta Rapid Transit Authority	HR	34.27%	
16	Bi-State Development Agency	LR	31.55%	
17	Denver Regional Transportation District	LR	31.12%	
18	Sacramento Regional Transit District	LR	30.21%	Low
19	Valley Metro Rail, Inc.	LR	28.08%	LR

Rank	Operator Name	Mode	Recovery (%)	Performance
20	Miami-Dade Transit	HR	23.40%	7
21	Central Puget Sound Regional Transit Authority	LR	23.22%	HR
22	San Francisco Municipal Railway	LR	22.51%	2
23	Maryland Transit Administration	HR	21.42%	
24	The Greater Cleveland Regional Transit Authority	LR	20.36%	
25	Charlotte Area Transit System	LR	20.02%	
26	Niagara Frontier Transportation Authority	LR	19.08%	
27	MTA Staten Island Railway	HR	18.30%	Poorest
28	Los Angeles County Metropolitan Transportation Authority	LR	18.30%	LR
29	The Greater Cleveland Regional Transit Authority	HR	18.03%	5
30	Maryland Transit Administration	LR	17.80%	HR
31	Port Authority of Allegheny County	LR	15.79%	2
32	Santa Clara Valley Transportation Authority	LR	15.19%	
33	Dallas Area Rapid Transit	LR	12.62%	
	System Mean		33.62%	

These values have been graphed in Figure 6-12:

Figure 6-12 Economic Recovery from Fares for Heavy Rail and Light Rail Transit Systems



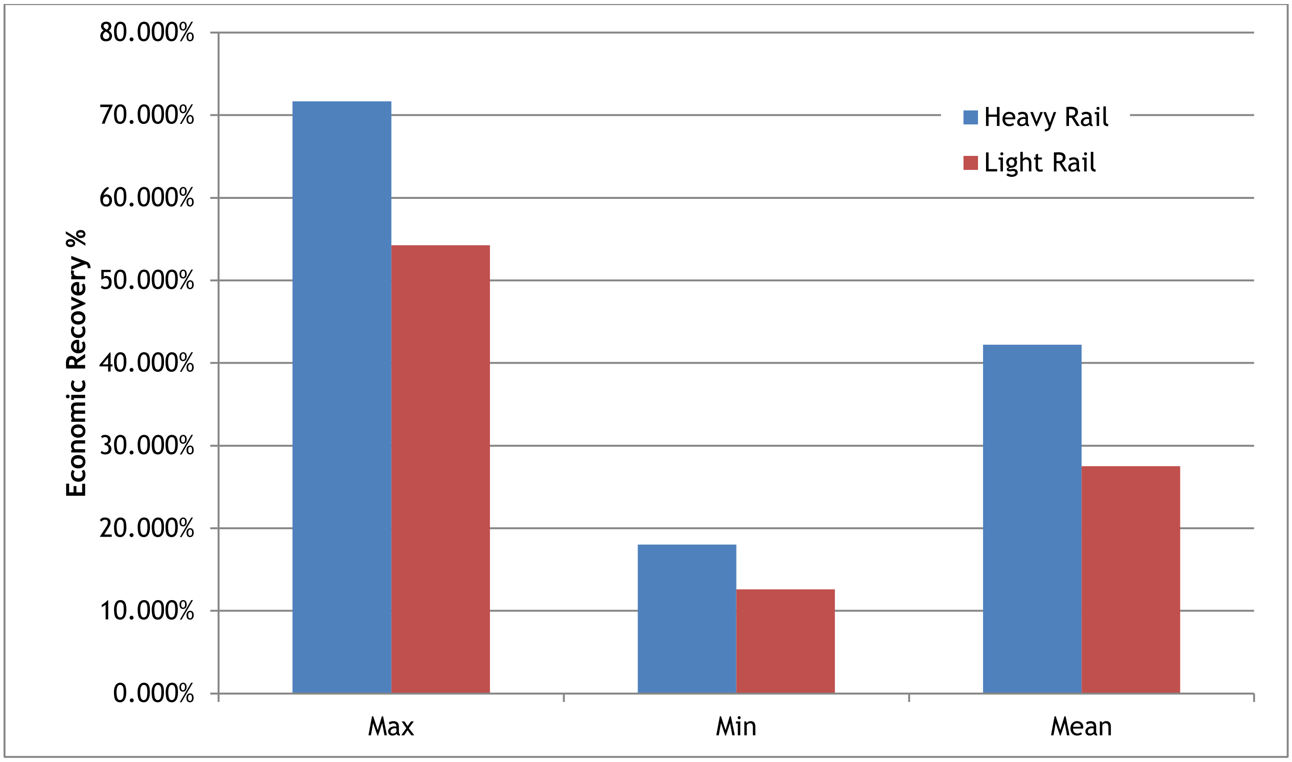
The maximum, minimum, and average values for economic recovery for heavy and LR systems, as well as the percent differences between the system sets are displayed in Table 6-26 Economic Recovery Ranges for Heavy Rail and Light Rail Transit Systems6.

Table 6-26 Economic Recovery Ranges for Heavy Rail and Light Rail Transit Systems

	Economic Recovery (%)				
	HR		LR		% Difference
Maximum	MTA New York City Transit	71.683%	San Diego Metropolitan Transit System	54.257%	27.673%
Minimum	The Greater Cleveland Regional Transit Authority	18.026%	Dallas Area Rapid Transit	12.621%	35.274%
Mean	42.205%		28.039%		40.335%
% Difference Max and Min	119.62%		124.51%		

These values are graphed in Figure 6-13.

Figure 6-13 Economic Recovery Ranges for Heavy Rail and Light Rail Transit Systems



Economic recovery performance varies between the system sets with HR systems generally attaining higher levels of performance. The highest performing HR system, MTA New York City Transit outperforms San Diego Metropolitan Transit System by 27.673%, while the lowest performing systems, The Greater Cleveland Regional Transit Authority and Dallas Area Rapid Transit, have a percent difference of 35.274%. The means of the system sets differ by 40.335% indicating the average performance of HR systems exceeds LR for economic recovery. In the highest performance category 6 systems are HR and only 2 are LR. Similar to the previous factors, the initial finding that HR systems offer superior performance will require additional follow up research as other factors such as fare policy and planning/operational details of the system influence revenue beyond mode choice.

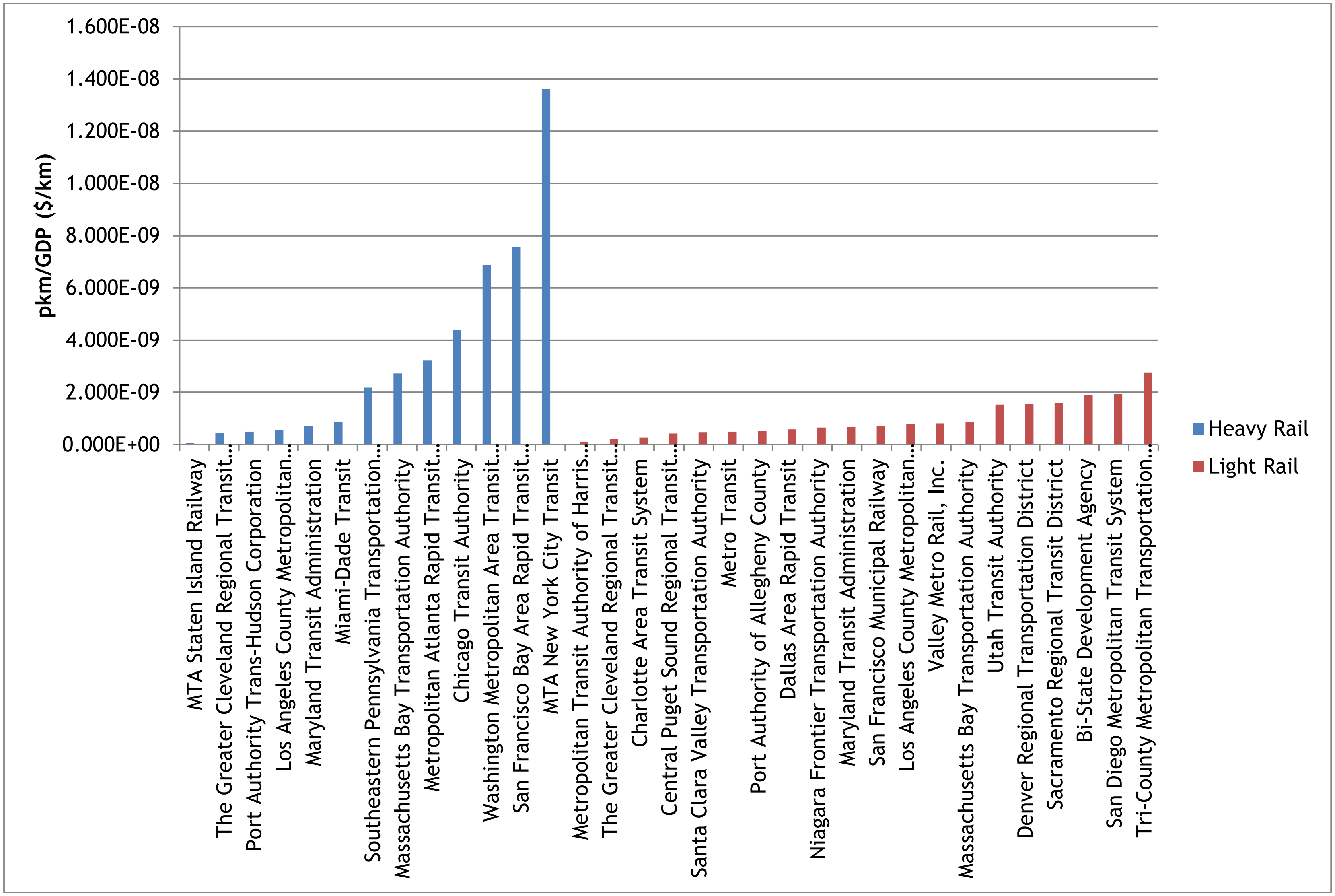
The final economic factor in this study is pkm/GDP, which measures the amount of transit utilization or transit travel generation with respect to economic activity in the region or city the transit system operates within. All systems have been ranked and are sorted by performance quartiles in Table 6-27 and graphed in Figure 6-14:

Table 6-27 pkm/GDP for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	PKM/GDP	Performance
1	MTA New York City Transit	HR	1.36E-08	Highest
2	San Francisco Bay Area Rapid Transit District	HR	7.57E-09	LR
3	Washington Metropolitan Area Transit Authority	HR	6.87E-09	1
4	Chicago Transit Authority	HR	4.38E-09	HR
5	Metropolitan Atlanta Rapid Transit Authority	HR	3.21E-09	7
6	Tri-County Metropolitan Transportation District of Oregon	LR	2.76E-09	
7	Massachusetts Bay Transportation Authority	HR	2.73E-09	
8	Southeastern Pennsylvania Transportation Authority	HR	2.18E-09	
9	San Diego Metropolitan Transit System	LR	1.93E-09	High
10	Bi-State Development Agency	LR	1.90E-09	LR
11	Sacramento Regional Transit District	LR	1.59E-09	8
12	Denver Regional Transportation District	LR	1.55E-09	HR
13	Utah Transit Authority	LR	1.53E-09	1
14	Miami-Dade Transit	HR	8.85E-10	
15	Massachusetts Bay Transportation Authority	LR	8.78E-10	
16	Valley Metro Rail, Inc.	LR	8.14E-10	
17	Los Angeles County Metropolitan Transportation Authority	LR	8.00E-10	
18	San Francisco Municipal Railway	LR	7.15E-10	Low
19	Maryland Transit Administration	HR	7.12E-10	LR
20	Maryland Transit Administration	LR	6.77E-10	6
21	Niagara Frontier Transportation Authority	LR	6.54E-10	HR
22	Dallas Area Rapid Transit	LR	5.81E-10	3
23	Los Angeles County Metropolitan Transportation Authority	HR	5.57E-10	
24	Port Authority of Allegheny County	LR	5.25E-10	
25	Metro Transit	LR	4.93E-10	

Rank	Operator Name	Mode	PKM/GDP	Performance
26	Port Authority Trans-Hudson Corporation	HR	4.93E-10	
27	Santa Clara Valley Transportation Authority	LR	4.80E-10	Poorest
28	The Greater Cleveland Regional Transit Authority	HR	4.42E-10	LR
29	Central Puget Sound Regional Transit Authority	LR	4.32E-10	5
30	Charlotte Area Transit System	LR	2.66E-10	HR
31	The Greater Cleveland Regional Transit Authority	LR	2.32E-10	2
32	Metropolitan Transit Authority of Harris County, Texas	LR	1.10E-10	
33	MTA Staten Island Railway	HR	6.32E-11	
System Mean			1.90E-09	

Figure 6-14 pkm/GDP for Heavy Rail and Light Rail Transit Systems



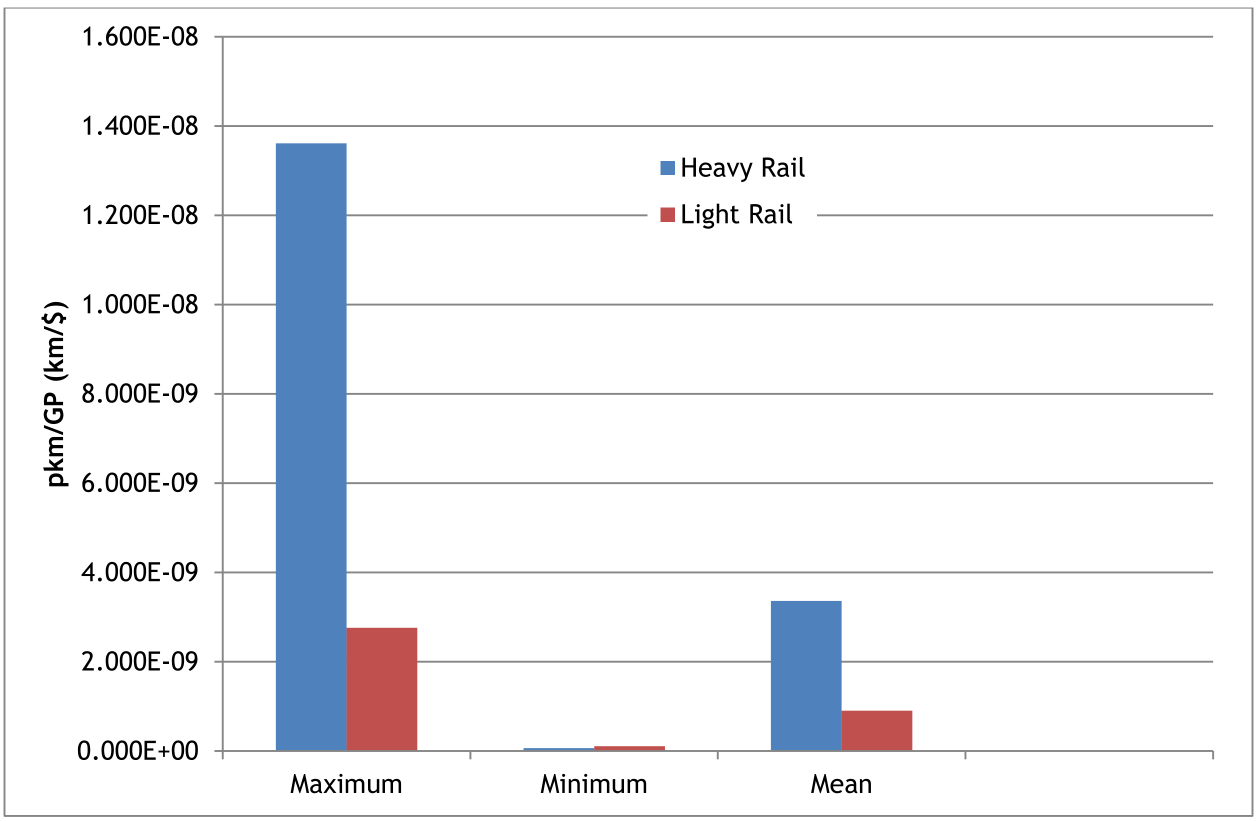
The maximum, minimum, and mean values for each system set along with percent differences within and between system sets are presented in Table 6-28.

Table 6-28 pkm/GDP ranges for Heavy Rail and Light Rail Transit Systems

	pkm/GDP ($/km)				
	HR		LR		% Difference
Maximum	MTA New York City Transit	1.361E-08	Tri-County Metropolitan Transportation District of Oregon	2.761E-09	132.545%
Minimum	MTA Staten Island Railway	6.320E-11	Metropolitan Transit Authority of Harris County, Texas	1.101E-10	54.115%
Mean	3.363E-09		9.464E-10		112.15%
% Difference Max and Min	198.15%		184.66%		

This data is displayed in Figure 6-15.

Figure 6-15 pkm/GDP Ranges for Heavy Rail and Light Rail Transit Systems



From this data, it can be observed that the HR systems in the NTD data set have higher performance for this factor, with 7 of 8 highest performing systems being HR systems. However, the high category systems are largely LR, with all but one of the remaining non-highest performance class HR systems occupying the lower two performance tiers.

Further, the highest performing system in HR (MTA New York) outperforms the LR system (Tri-County Metropolitan Transportation District of Oregon) by a percent difference of 132.545%. In the low performance category, the HR system also achieves higher performance with a percent difference of 54.115%. The mean factor scores also result in a higher performance of HR with a percent difference of 112.15%. However, it is worth noting that HR systems in general have higher pkm and serve areas with higher GDP levels – which is displayed in Table 6-29:

Table 6-29 Average pkm and GDP for Heavy Rail and Light Rail Transit Systems

Mean PKM (km)	**Mean GDP ($)**
HR (excluding MTA New York): 879,955,392.71	HR: $505,313,384,615.39
HR: 2,014,297,817.16	
LR (excluding Charlotte Area Transit System): 151,925,021.59	LR: $191,703,200,000.00
LR: 158,143,445.48	

From Table 6-29, the general overall superior performance of HR over LR in the highest performance category can be commented upon through ratios. While the average pkm of the HR category is larger than the average GDP of the LR category, so is the average pkm. The ratios are:

- HR/LR pkm with extreme values removed: 5.79
- HR/LR pkm with extreme values: 12.74
- HR/LR GDP: 2.63

With this rudimentary analysis, it can be seen that the much greater level of pkm attained by HR systems, on average, compensates for the higher average GDP of the areas served by the systems. This can explain the general superior performance of HR systems for the pkm/GDP factor for the NTD data set systems – however, further analysis is needed to understand the causation of this superior performance. This factor aims to comment on the sustainability of the system for prevailing economic conditions through its ability to create ridership.

It is important to note that this research is not focussing on transit-economic contributions at this stage, but rather on benchmarking performance to determine if performance patterns emerge in order to comment on the sustainability of different transit systems. This factor does not seek to establish a link between economic development and transit usage – it is not insinuating that HR systems or higher transit usage stimulate economic development. Rather, it is solely measuring transit utilization in relation to economic activity in the area served by transit. In this case, for example, it could be argued that for a decision maker benchmarking to improve LR service relative to economic sustainability in Metropolitan Transit Authority of Harris County, Texas, improving the amount of ridership and pkm relative to economic output in the service area could be a key factor. However, given the complexity of economic analysis, this research does not comment on the ability of transit to increase or decrease GDP.

To summarize and conclude, throughout all economic factors, further research is required to determine causes of performance differences between modes. Five economic factors have been analyzed and performance levels have been set for 33 transit systems from the NTD database – operating cost, average travel time, average fare, recovery %, and pkm/GDP. In these factors, mixed performance results were attained, with neither mode attaining a dominant performance standard throughout the various analyses conducted. However, in general, HR systems were found to achieve all around better performance in the highest performance category throughout all factors except average fare cost. The results of analysis for each factor are outlined in Table 6-30:

Table 6-30 Summary of Economic Analysis

	Highest Performance Systems	Lowest Performance Systems	Mean	Trend
Operating Cost	HR systems achieve better performance than LR.	HR systems perform slightly better than LR systems.	HR mean value indicates better performance.	LR trend line indicates higher efficiency
Average Travel Time	HR systems achieve much greater performance than LR.	HR systems achieve better performance than LR.	HR mean value indicates better performance.	N/A
Average User Fare	LR systems achieve slightly greater performance than HR.	LR attains greater performance than HR.	LR mean value indicates better performance.	N/A
Recovery %	HR systems achieve better performance than LR.	HR systems perform slightly better than LR systems.	HR mean value indicates better performance.	N/A
pkm/GDP	HR systems achieve better performance than LR.	HR systems perform slightly better than LR systems.	HR mean value indicates better performance.	N/A

Overall results indicate that in general, HR systems perform better overall in the economic analysis than LR systems. This can be observed in factor by factor analysis where HR outperforms LR under 4/5 factors. First, for the operating cost/pkm factor, HR follows a distribution of 6,2,4,1 and LR follows a distribution of 2,7,5,6. Both system sets have the majority of their systems in the higher two tiers, however HR is better represented in the highest performance tier. Average travel time has a HR distribution of 7,3,2,1 and LR distribution of 1,6,7,6. HR is most represented in the top categories, while LR is most represented in the lowest, indicating better HR performance. Next, for the average user fare factor, HR systems follow a 2, 4, 2, 5 distribution, with most systems falling into the lowest two categories, while LR follow a 6,5,7,2 distribution with most systems in the highest two categories. This represents higher performance by LR systems. Under the Fare Recovery factor HR had a 6,3, 2, 2 distribution, with the most systems in the highest performance categories. While LR has a distribution of 2,6,7,5, with the middle categories representing the majority of the systems. These distributions indicate general greater performance by HR systems. For the pkm/GDP factor, HR systems showed a 7,1,3,2 distribution, with the highest performance categories having the greatest representation of systems, while LR had a 1,8,6,5 with the middle performance categories having the greatest representation of systems. This indicates that in general, HR offered better performance for this factor. However, in factor 3, average fare, LR systems do in general outperform HR systems.

There is a gradient present in performance, meaning that regardless of mode, systems can attain a high degree of performance across all factors. When generalized, HR systems are able to achieve better results. This conclusion is a statement of correlation, not a statement of causality. Again, all factors are based on a variety of variables that are outside of the scope of this study, meaning future research needs to account for this limitation.

6.5.3 Social Factors

In this methodology, three social factors were successfully computed using the NTD dataset with some expansion. No factors are explicitly normalized. These factors all assess accessibility in a unique way and are system accessibility, affordability, and average journey length, which all reflect the transit system’s social sustainability. Health impacts as well as more nuanced accessibility factors were not included in this section of the study due to data limitations. The first factor, system accessibility, reflects how well the transit system is integrated into the broader urban area and is a proxy for the system's ability to serve a diversity of trip needs. The second factor is a proxy for accessibility through an economic exclusion lens by looking at how users may be unable to pay and therefore excluded from using transit thus incurring social costs, this factor relies on the same GDP data utilized in the economic section. The final factor, average journey length measures accessibility from an individual lens based on the individual journey length a user must travel to meet their needs. Table 6-31 displays the factors for all systems separated by mode.

Table 6-31 Social Factors for Heavy Rail and Light Rail Transit Systems

	Operator Name	System Accessibility	Affordability (fare/per capita GDP)	Average Journey Length (km)	User Accessibility
HR (HR)	Massachusetts Bay Transportation Authority	0.043	1.762E-05	5.585	92.45%
	MTA New York City Transit	2.489	1.619E-05	6.406	18.80%
	Port Authority Trans-Hudson Corporation	0.073	2.076E-05	6.818	53.85%
	MTA Staten Island Railway	0.188	1.406E-05	9.501	21.74%
	Southeastern Pennsylvania Transportation Authority	0.586	1.710E-05	7.134	40.00%
	Washington Metropolitan Area Transit Authority	0.223	2.474E-05	9.164	100.00%
	Maryland Transit Administration	0.025	1.796E-05	6.897	100.00%
	Metropolitan Atlanta Rapid Transit Authority	0.045	1.613E-05	10.211	100.00%
	Miami-Dade Transit	0.015	2.447E-05	11.894	100.00%
	The Greater Cleveland Regional Transit Authority	0.014	2.449E-05	11.392	72.22%
	Chicago Transit Authority	1.003	2.254E-05	9.896	62.94%
	San Francisco Bay Area Rapid Transit District	0.508	4.489E-05	20.669	100.00%
	Los Angeles County Metropolitan Transportation Authority	0.007	1.397E-05	7.792	100.00%
LR (LR)	Tri-County Metropolitan Transportation District of Oregon	0.173	1.590E-05	7.915	100.00%
	Central Puget Sound Regional Transit Authority	0.153	2.011E-05	11.585	100.00%
	Massachusetts Bay Transportation Authority	0.014	1.702E-05	3.815	48.65%

Operator Name	System Accessibility	Affordability (fare/per capita GDP)	Average Journey Length (km)	User Accessibility
Niagara Frontier Transportation Authority	0.212	2.049E-05	4.218	100.00%
Port Authority of Allegheny County	0.014	2.581E-05	7.723	100.00%
Maryland Transit Administration	0.024	1.818E-05	10.872	100.00%
Charlotte Area Transit System	0.032	1.680E-05	8.479	100.00%
The Greater Cleveland Regional Transit Authority	0.007	2.449E-05	9.460	26.47%
Metro Transit	0.016	1.799E-05	8.518	100.00%
Metropolitan Transit Authority of Harris County, Texas	0.003	9.176E-06	3.664	100.00%
Dallas Area Rapid Transit	0.013	1.457E-05	11.339	100.00%
Bi-State Development Agency	0.049	2.616E-05	13.914	100.00%
Utah Transit Authority	0.173	1.452E-05	6.873	100.00%
Denver Regional Transportation District	0.087	1.942E-05	11.169	100.00%
Santa Clara Valley Transportation Authority	0.078	9.676E-06	8.253	100.00%
San Francisco Municipal Railway	2.060	1.131E-05	4.280	100.00%
Sacramento Regional Transit District	0.100	2.432E-05	8.668	97.92%
San Diego Metropolitan Transit System	0.000	2.162E-05	9.851	100.00%
Los Angeles County Metropolitan Transportation Authority	0.011	1.267E-05	11.559	100.00%
Valley Metro Rail, Inc.	0.023	1.848E-05	11.647	100.00%

The first factor, system accessibility, has been calculated for all systems and has been displayed in Table 6-32 sorted by performance quartile.

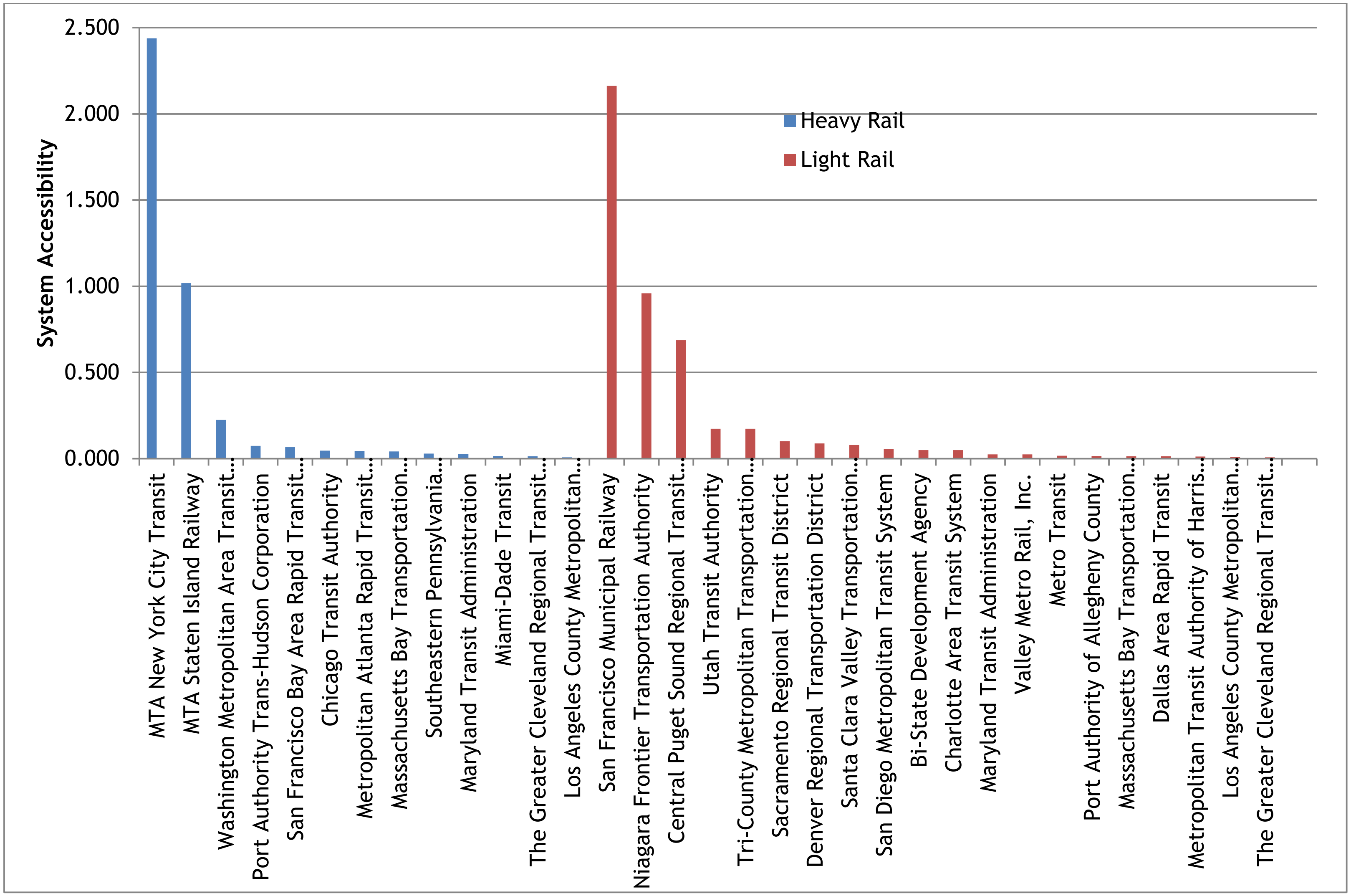
Table 6-32 System Accessibility Ranking for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	System accessibility	Performance
1	MTA New York City Transit	HR	2.439	Highest
2	San Francisco Municipal Railway	LR	2.163	LR
3	MTA Staten Island Railway	HR	1.018	5
4	Niagara Frontier Transportation Authority	LR	0.959	HR
5	Central Puget Sound Regional Transit Authority	LR	0.686	3
6	Washington Metropolitan Area Transit Authority	HR	0.223	
7	Utah Transit Authority	LR	0.173	
8	Tri-County Metropolitan Transportation District of Oregon	LR	0.173	
9	Sacramento Regional Transit District	LR	0.100	High
10	Denver Regional Transportation District	LR	0.087	LR
11	Santa Clara Valley Transportation Authority	LR	0.078	6
12	Port Authority Trans-Hudson Corporation	HR	0.073	HR
13	San Francisco Bay Area Rapid Transit District	HR	0.066	3
14	San Diego Metropolitan Transit System	LR	0.055	
15	Bi-State Development Agency	LR	0.049	
16	Charlotte Area Transit System	LR	0.049	
17	Chicago Transit Authority	HR	0.046	
18	Metropolitan Atlanta Rapid Transit Authority	HR	0.045	Low
19	Massachusetts Bay Transportation Authority	HR	0.040	LR
20	Southeastern Pennsylvania Transportation Authority	HR	0.028	3
21	Maryland Transit	HR	0.025	HR

Rank	Operator Name	Mode	System accessibility	Performance
	Administration			
22	Maryland Transit Administration	LR	0.024	5
23	Valley Metro Rail, Inc.	LR	0.023	
24	Metro Transit	LR	0.016	
25	Miami-Dade Transit	HR	0.015	
26	Port Authority of Allegheny County	LR	0.014	Poorest
27	The Greater Cleveland Regional Transit Authority	HR	0.014	LR
28	Massachusetts Bay Transportation Authority	LR	0.014	6
29	Dallas Area Rapid Transit	LR	0.013	HR
30	Metropolitan Transit Authority of Harris County, Texas	LR	0.012	2
31	Los Angeles County Metropolitan Transportation Authority	LR	0.011	
32	Los Angeles County Metropolitan Transportation Authority	HR	0.007	
33	The Greater Cleveland Regional Transit Authority	LR	0.007	
System Mean			0.27	

Accessibility scores are also displayed by system in Figure 6-16.

Figure 6-16 System Accessibility for Heavy and Light Rail Transit Systems



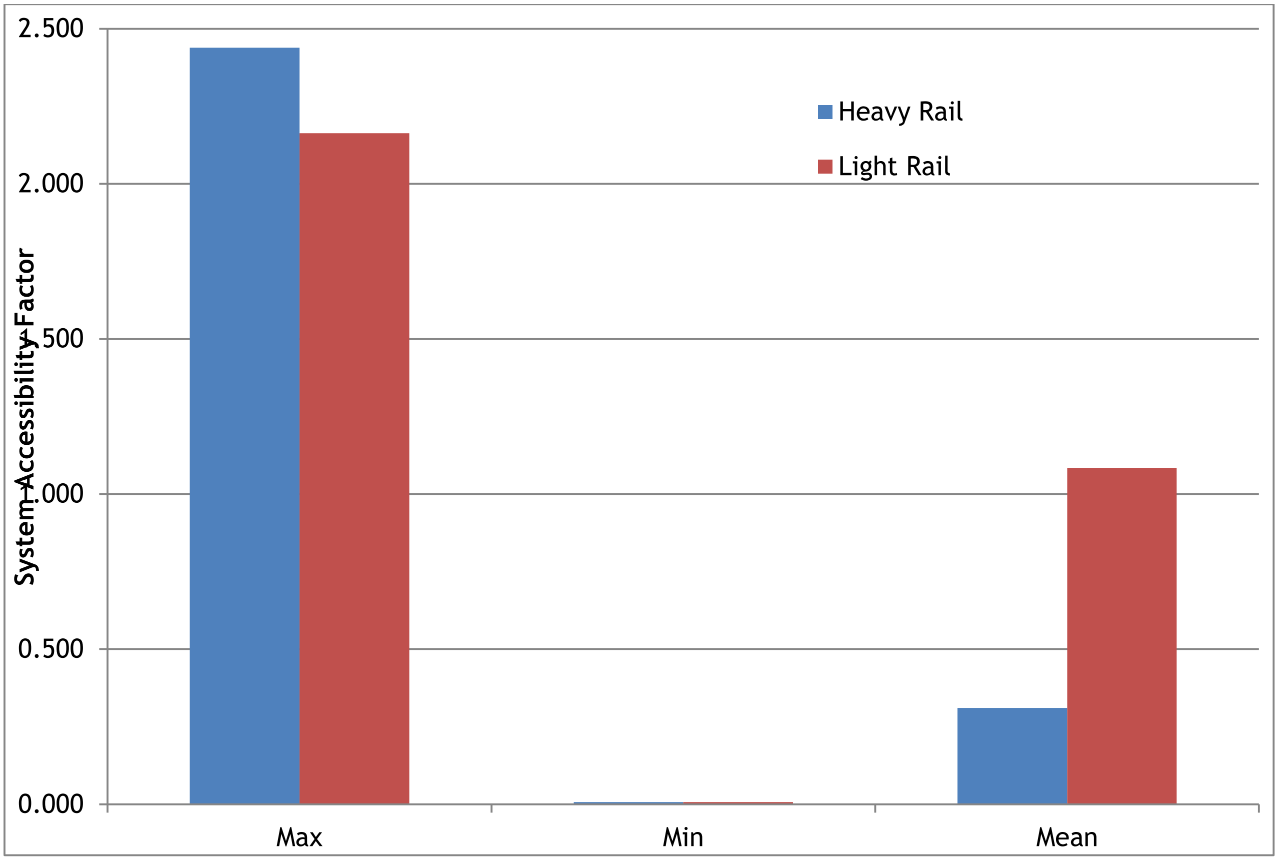
The maximum, minimum, and mean for each system set along with the percent difference between and within system sets are shown in Table 6-33.

Table 6-33 Accessibility Ranges for Heavy Rail and Light Rail Transit Systems

	System Accessibility				
	HR		LR		% Difference
Maximum	MTA New York City Transit	2.439	San Francisco Municipal Railway	2.163	11.991%
Minimum	Los Angeles County Metropolitan Transportation Authority	0.00733	The Greater Cleveland Regional Transit Authority	0.00732	0.166%
Mean	0.311		1.085		110.950%
% Difference Max and Min	198.80%		198.65%		

These ranges have also been graphed in Figure 6-17.

Figure 6-17 Accessibility Factor for Heavy Rail and Light Rail Transit Systems



It can be observed from the graphs and tables that LR systems in general have achieved better performance for the system accessibility factor. In terms of highest performing systems, LR systems attained 5 of the highest ranking spot. In the second highest performance category, LR systems achieved greater performance, with only 2 HR system present. MTA New York city, the highest performing HR system, and San Francisco Municipal Railway had a percent difference of 11.991% greater, but not vastly superior performance by the top HR system. For the lowest performing systems, LA metro outperformed The Greater Cleveland Regional Transit Authority with a percent difference of 0.166%. The means of each system sets had a percent difference of 58.432%, favouring HR systems. While the highest performing maximum and minimum systems are HR, LR populated the higher performance categories.

From these figures and graphs, in general Light Rail systems have achieved better performance for the accessibility factor better than HR systems for the NTD data set.

Future studies should use a more rigorous indicator for accessibility as outlined in the literature review, such as a cumulative opportunity indicator to better reflect accessibility. However, for this high level review and demonstration of sustainability and comparison of modes this indicator is useful - as for other indicators, detailed data and model outputs would be required that are outside of the scope of this study.

This indicator (pkm per capita/urban area) represents the number of passenger km travelled per citizen on average per unit of area in the jurisdiction served by the system. This is a proxy indicator for the system's accessibility. The results show that, in general, highest performing HR systems are able to generate the highest pkm per person per unit area, with highest performing LR placing in the second performance category. Lower performing HR and LR have similar performance. Density was cited in the literature review as a key determinant of transit usage and access to investigate the impact of density on the accessibility factor, the densities of each system along with the accessibility factor for each system are shown in Table 6-34.

Table 6-34 Density and System Accessibility for Heavy Rail and Light Rail Transit Systems

Rank	Mode	Operator Name	City or MSA	System accessibility	MSA or Urban Density (people/km^2)
1	HR	MTA New York City Transit	New York	2.43857	10429.56
2	LR	San Francisco Municipal Railway	San Francisco	2.16269	6632.90
3	HR	Staten Island Rapid Transit Operating Authority	New York	1.01783	3105.39
4	HR	Chicago Transit Authority	Chicago	1.00321	1510.93
5	LR	Niagara Frontier Transportation Authority	Buffalo	0.95920	2498.32
6	LR	Central Puget Sound Regional Transit Authority	Seattle	0.68567	2799.59
7	HR	Southeastern Pennsylvania	Philadelphia	0.58592	1104.48

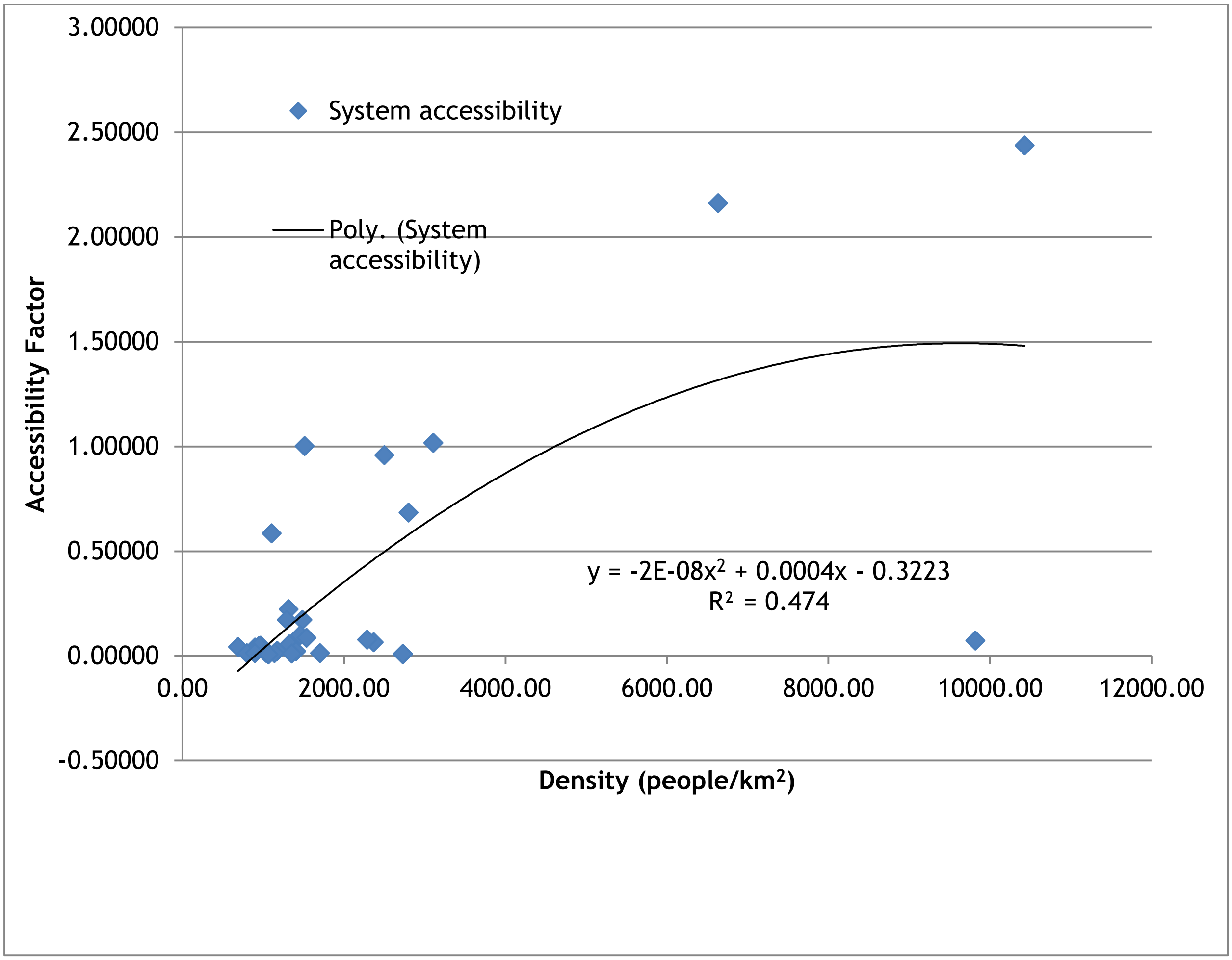
Rank	Mode	Operator Name	City or MSA	System accessibility	MSA or Urban Density (people/km^2)
		Transportation Authority			
8	HR	Washington Metropolitan Area Transit Authority	Washington	0.22334	1312.79
9	LR	Utah Transit Authority	Salt Lake City	0.17342	1483.65
10	LR	Tri-County Metropolitan Transportation District of Oregon	Portland	0.17288	1289.56
11	LR	Sacramento Regional Transit District	Sacramento	0.09970	1458.08
12	LR	Denver Regional Transportation District	Denver	0.08746	1535.81
13	LR	Santa Clara Valley Transportation Authority	San Jose	0.07768	2284.40
14	HR	Port Authority Trans-Hudson Corporation	New York, Newark, Harrison, Hoboken, and Jersey City	0.07342	9820.89
15	HR	San Francisco Bay Area Rapid Transit District	San Francisco-Oakland-Fremont	0.06638	2365.41
16	LR	San Diego Metropolitan Transit System	San Diego	0.05541	1320.47
17	LR	Bi-State Development Agency	St. Louis	0.04937	967.66
18	LR	Charlotte Area Transit System	Charlotte	0.04887	948.69
19	HR	Metropolitan Atlanta Rapid Transit Authority	Atlanta	0.04461	688.38
20	HR	Massachusetts Bay Transportation Authority	Boston	0.04042	896.86
21	HR	Maryland Transit Administration	Baltimore	0.02510	1173.77
22	LR	Maryland Transit	Baltimore	0.02389	1173.77

Rank	Mode	Operator Name	City or MSA	System accessibility	MSA or Urban Density (people/km^2)
		Administration			
23	LR	Valley Metro Rail, Inc.	Phoenix	0.02345	1404.78
24	LR	Metro Transit	Minneapolis	0.01610	1031.59
25	HR	Miami-Dade Transit	Miami	0.01453	1701.84
26	LR	Port Authority of Allegheny County	Pittsburgh	0.01399	794.47
27	HR	The Greater Cleveland Regional Transit Authority	Cleveland	0.01392	1066.19
28	LR	Massachusetts Bay Transportation Authority	Boston	0.01378	896.86
29	LR	Dallas Area Rapid Transit	Dallas	0.01336	1137.63
30	LR	Metropolitan Transit Authority of Harris County, Texas	Houston	0.01193	1351.93
31	LR	Los Angeles County Metropolitan Transportation Authority	Los Angeles	0.01053	2728.98
32	HR	Los Angeles County Metropolitan Transportation Authority	Los Angeles	0.00733	2728.98
33	LR	The Greater Cleveland Regional Transit Authority	Cleveland	0.00732	1066.19

Urban or Discrete Area and Population (census)
MSA Area (NTD)

As mentioned previously, systems that serve only an urban area or a discrete area utilize the area and population figures from the census for that area for the calculation, while systems that serve a broader metropolitan area utilize figures from the NTD for the calculation. These values are shown in Figure 6-18.

Figure 6-18 Accessibility Factor as a Function of Density



There is a small trend tying this accessibility factor to density, as indicated by a low r^2 value and general scattered data, however the data does not match the trend strongly. This is in line with literature review findings (such as discussions put forward by Kenworthy and Newman (1999), Schiller, Bruun, and Kenworthy (2003), and Banister (2008)) on policy and past research tying accessible transport for generating trips and linking transport into land use with denser cities, however, the trend is not strongly established and further research needs to be conducted on the application of this type of accessibility factor over other accessibility factors such as time of day or GIS based factors.

The next factor, affordability, represents the unit-less ratio of fare over per capita income as a proxy for affordability indicating the systems access. The ranking for all systems is displayed in Table 6-35.

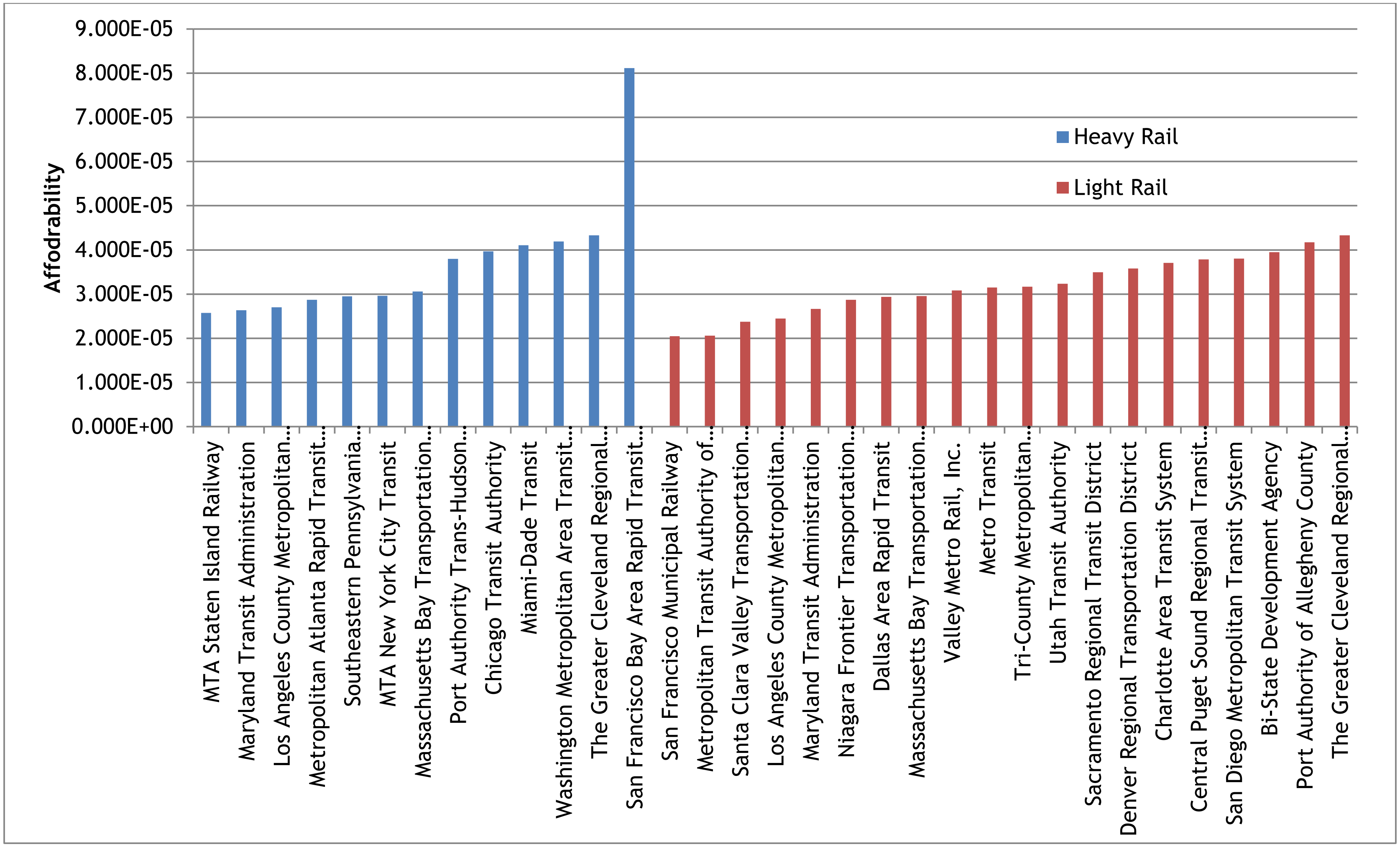
Table 6-35 Affordability Factor for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	Affordability Fare/(income per capita)	Performance
1	San Francisco Municipal Railway	LR	2.05E-05	Highest
2	Metropolitan Transit Authority of Harris County, Texas	LR	2.06E-05	LR
3	Santa Clara Valley Transportation Authority	LR	2.38E-05	5
4	Los Angeles County Metropolitan Transportation Authority	LR	2.45E-05	HR
5	MTA Staten Island Railway	HR	2.57E-05	3
6	Maryland Transit Administration	HR	2.64E-05	
7	Maryland Transit Administration	LR	2.67E-05	
8	Los Angeles County Metropolitan Transportation Authority	HR	2.70E-05	
9	Metropolitan Atlanta Rapid Transit Authority	HR	2.87E-05	High
10	Niagara Frontier Transportation Authority	LR	2.87E-05	LR
11	Dallas Area Rapid Transit	LR	2.94E-05	5
12	Southeastern Pennsylvania Transportation Authority	HR	2.95E-05	HR
13	Massachusetts Bay Transportation Authority	LR	2.95E-05	4
14	MTA New York City Transit	HR	2.96E-05	
15	Massachusetts Bay Transportation Authority	HR	3.06E-05	
16	Valley Metro Rail, Inc.	LR	3.08E-05	
17	Metro Transit	LR	3.15E-05	
18	Tri-County Metropolitan Transportation District of Oregon	LR	3.17E-05	Low
19	Utah Transit Authority	LR	3.24E-05	LR
20	Sacramento Regional Transit District	LR	3.50E-05	7
21	Denver Regional Transportation District	LR	3.58E-05	HR
22	Charlotte Area Transit System	LR	3.71E-05	1
23	Central Puget Sound Regional Transit Authority	LR	3.79E-05	

Rank	Operator Name	Mode	Affordability Fare/(income per capita)	Performance
24	Port Authority Trans-Hudson Corporation	HR	3.80E-05	
25	San Diego Metropolitan Transit System	LR	3.81E-05	
26	Bi-State Development Agency	LR	3.95E-05	Poorest
27	Chicago Transit Authority	HR	3.96E-05	LR
28	Miami-Dade Transit	HR	4.11E-05	3
29	Port Authority of Allegheny County	LR	4.17E-05	HR
30	Washington Metropolitan Area Transit Authority	HR	4.19E-05	5
31	The Greater Cleveland Regional Transit Authority	LR	4.33E-05	
32	The Greater Cleveland Regional Transit Authority	HR	4.33E-05	
33	San Francisco Bay Area Rapid Transit District	HR	8.12E-05	
System Mean			3.40E-05	

These values are graphed by system in Figure 6-19.

Figure 6-19 Affordability Factor for Heavy Rail and Light Rail Transit Systems



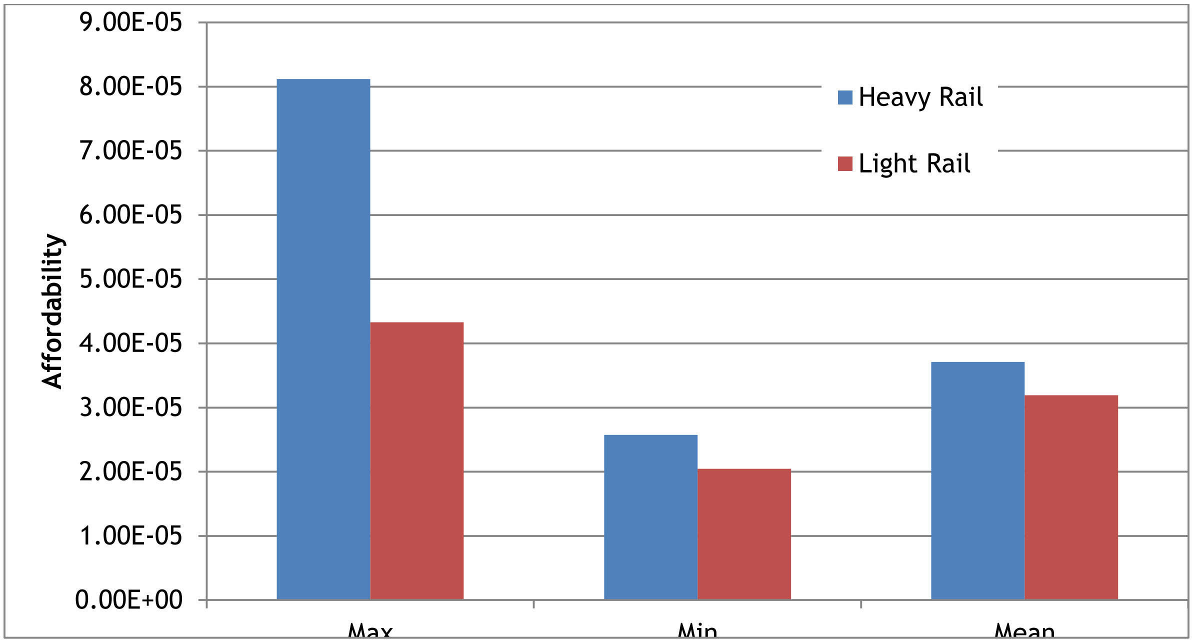
The maximum, minimum, and mean values for the affordability ratio have also been calculated and are displayed in Table 6-36.

Table 6-36 System Affordability Factor Ranges for Heavy and Light Rail Transit Systems

	System Affordability				
	HR		LR		% Difference
Maximum	San Francisco Bay Area Rapid Transit District	8.12E-05	The Greater Cleveland Regional Transit Authority	4.33E-05	60.849%
Minimum	MTA Staten Island Railway	2.57E-05	San Francisco Municipal Railway	2.05E-05	22.801%
Mean	3.71E-05		3.19E-05		15.081%
% Difference Max and Min	103.75%		71.67%		

These ranges are graphed in Figure 6-20.

Figure 6-20 Affordability Ranges for Heavy and Light Rail Transit Systems



As the influences on per capita income are outside of the scope of this research, this factor is observed and measured for each system and general trends are commented on in order to complete the sustainability measurement and analysis. Based on the factor sorting and graphing, rudimentary analysis can be conducted. From the performance categorization, it can be observed that in general, LR systems offer higher levels of performance than HR systems for the affordability index with 5 out of 8 highest performers being LR Systems, and 5 out of 9 high performers being LR. Seven HR systems are in the top two performance categories, while the remaining 6 are in the bottom two indicating a blend of performance from the system set in the NTD.

As this indicator is based on the user cost per trip indicator, similar performance between indicators is expected. However, many systems shifted in ranking due to the influence of income per capita. A comparison of ranking is shown in Table 6-37.

Table 6-37 Comparison of Fare and Affordability Ranking

Mode	Operator	User Fare Cost Rank	Affordability Rank
LR	Metropolitan Transit Authority of Harris County, Texas	1	2
LR	Los Angeles County Metropolitan Transportation Authority	2	8
LR	Niagara Frontier Transportation Authority	3	10
HR	Los Angeles County Metropolitan Transportation Authority	4	8
HR	Metropolitan Atlanta Rapid Transit Authority	5	9
LR	Valley Metro Rail, Inc.	6	16
LR	San Francisco Municipal Railway	7	1
LR	Utah Transit Authority	8	19
LR	Dallas Area Rapid Transit	9	11
HR	MTA Staten Island Railway	10	5
HR	Maryland Transit Administration	11	6
LR	Maryland Transit Administration	12	7
LR	Tri-County Metropolitan Transportation District of Oregon	13	18
LR	Santa Clara Valley Transportation Authority	14	3
HR	Southeastern Pennsylvania Transportation Authority	15	12
LR	Sacramento Regional Transit District	16	20
HR	MTA New York City Transit	17	14
LR	Charlotte Area Transit System	18	22
LR	Metro Transit	19	17
HR	Miami-Dade Transit	20	28
LR	Massachusetts Bay Transportation Authority	21	13
LR	Bi-State Development Agency	22	26
LR	San Diego Metropolitan Transit System	23	25
HR	Massachusetts Bay Transportation Authority	24	15
LR	Denver Regional Transportation District	25	21
LR	The Greater Cleveland Regional Transit Authority	26	31
HR	The Greater Cleveland Regional Transit Authority	27	32

Mode	Operator	User Fare Cost Rank	Affordability Rank
LR	Port Authority of Allegheny County	28	29
HR	Chicago Transit Authority	29	27
LR	Central Puget Sound Regional Transit Authority	30	23
HR	Port Authority Trans-Hudson Corporation	31	24
HR	Washington Metropolitan Area Transit Authority	32	30
HR	San Francisco Bay Area Rapid Transit District	33	33

As noted, 32 systems changed ranking with 17 systems changing performance category, indicating the influence of income per capita on this factor. This is expected as this indicator is not a pure measure of cost, but rather a proxy indicator for how accessible systems are based on affordability. However, even with changes in performance the overall performance trend by performance category still demonstrates higher performance for LR systems.

Based on the performance ranges, for the highest performing systems of both types, the LR system, San Francisco Municipal Railway, offers the best performance compared to the HR alternative, Staten Island Railway, with a percent difference of 22.801%. Out of the lowest performing systems, The Greater Cleveland Regional Transit Authority outperforms the San Francisco Bay Area Rapid Transit District with a percent difference of 60.849%. The mean performance value of the LR system is also superior with a percent difference of 15.081%.

To continue exploring the difference in performance between system sets, the average income per capita and fare for each system sets will be used.

- HR Income per Capita: $31,486.61
- HR User Fare Costs: $1.19
- LR Income per Capita: $29,114.15
- LR User Fare Costs: $0.91
- HR/LR Income Ratio: 1.08
- HR/LR Fare Ratio:1.101

LR systems have on average lower costs per trip as well as lower per capita income. It can be observed that while the HR system MSAs have on average larger income per capita, they also have on average larger fares, which as shown in the ratios are larger by ratio than the per capita income.

As fare determination is a complicated process (see previous discussion on fare) and income in a MSA is also a complex matter, this factor is not discussed at length in this thesis, but is included for the complete analysis of mass transit systems. It is not implied that LR or HR systems on average have impact on income per capita.

The next factor, average journey length, is a proxy for user accessibility and represents the average length users must utilize the system to access activities, employment, or their household. The factors have been sorted by performance category and are represented in Table 6-38.

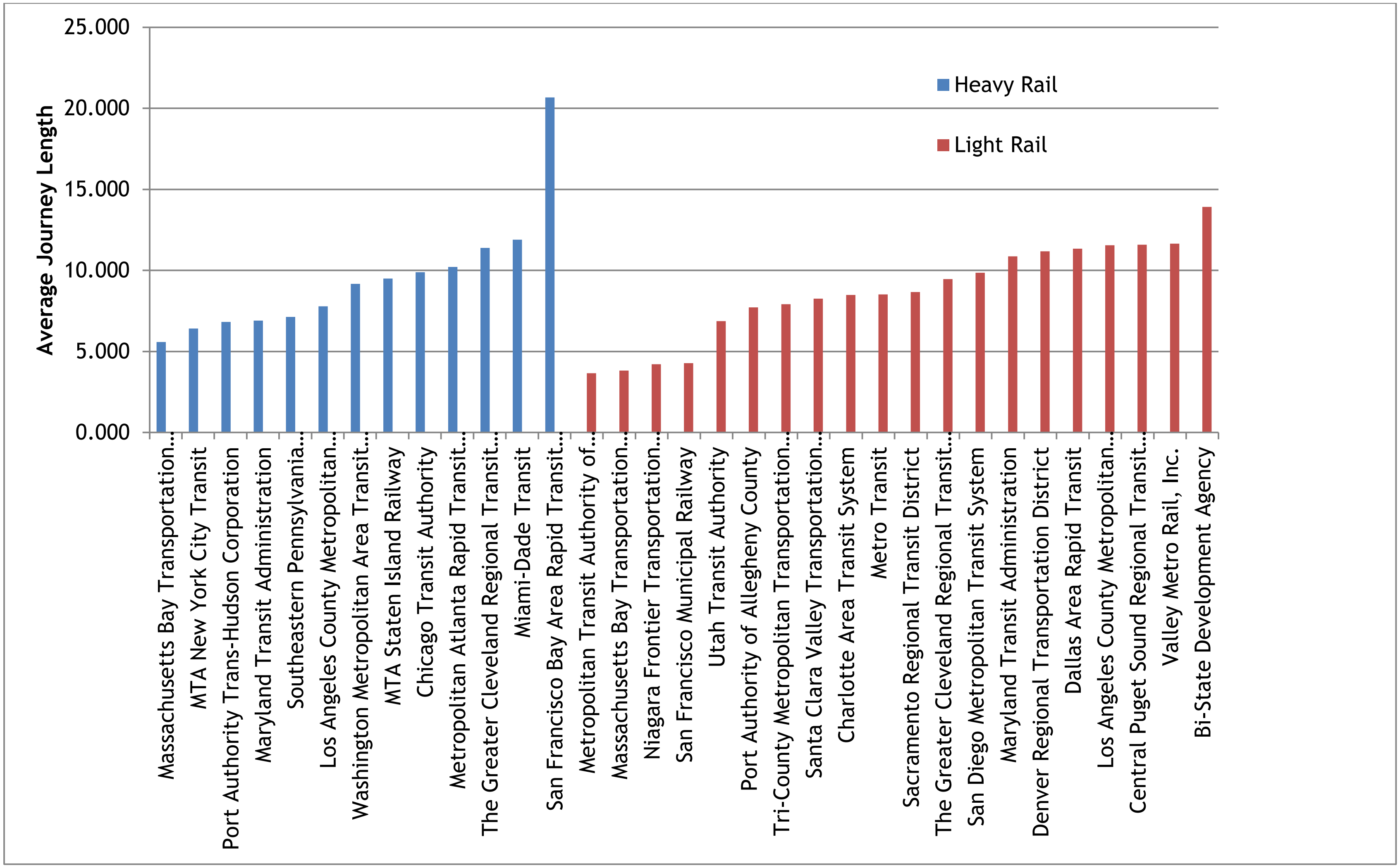
Table 6-38 Average Journey Length for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	Average Journey Length (km)	Performance
1	Metropolitan Transit Authority of Harris County, Texas	LR	3.66	Highest
2	Massachusetts Bay Transportation Authority	LR	3.82	LR
3	Niagara Frontier Transportation Authority	LR	4.22	5
4	San Francisco Municipal Railway	LR	4.28	HR
5	Massachusetts Bay Transportation Authority	HR	5.58	3
6	MTA New York City Transit	HR	6.41	
7	Port Authority Trans-Hudson Corporation	HR	6.82	
8	Utah Transit Authority	LR	6.87	
9	Maryland Transit Administration	HR	6.90	High
10	Southeastern Pennsylvania Transportation Authority	HR	7.13	LR
11	Port Authority of Allegheny County	LR	7.72	6
12	Los Angeles County	HR	7.79	HR

Rank	Operator Name	Mode	Average Journey Length (km)	Performance
	Metropolitan Transportation Authority			
13	Tri-County Metropolitan Transportation District of Oregon	LR	7.91	3
14	Santa Clara Valley Transportation Authority	LR	8.25	
15	Charlotte Area Transit System	LR	8.48	
16	Metro Transit	LR	8.52	
17	Sacramento Regional Transit District	LR	8.67	
18	Washington Metropolitan Area Transit Authority	HR	9.16	Low
19	The Greater Cleveland Regional Transit Authority	LR	9.46	LR
20	MTA Staten Island Railway	HR	9.50	4
21	San Diego Metropolitan Transit System	LR	9.85	HR
22	Chicago Transit Authority	HR	9.90	4
23	Metropolitan Atlanta Rapid Transit Authority	HR	10.21	
24	Maryland Transit Administration	LR	10.87	
25	Denver Regional Transportation District	LR	11.17	
26	Dallas Area Rapid Transit	LR	11.34	Poorest
27	The Greater Cleveland Regional Transit Authority	HR	11.39	LR
28	Los Angeles County Metropolitan Transportation Authority	LR	11.56	5
29	Central Puget Sound Regional Transit Authority	LR	11.59	HR
30	Valley Metro Rail, Inc.	LR	11.65	3
31	Miami-Dade Transit	HR	11.89	
32	Bi-State Development Agency	LR	13.91	
33	San Francisco Bay Area Rapid Transit District	HR	20.67	
System Mean			9.00	

These values are graphed in Figure 6-21

Figure 6-21 Average Journey Length for Heavy Rail and Light Rail Transit Systems



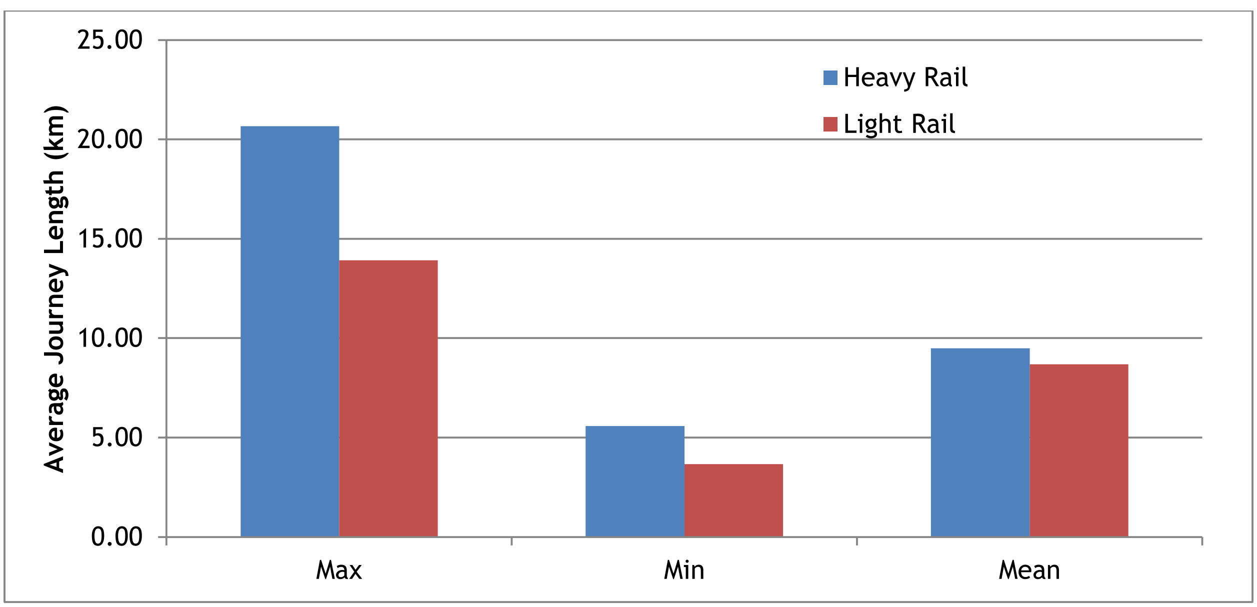
The data set for this factor has been sorted into performance ranges that are displayed in Table 6-39

Table 6-39 Average Journey Length Ranges for Heavy Rail and Light Rail Transit Systems

	Average Journey Length				
	HR		LR		% Difference
Maximum	San Francisco Bay Area Rapid Transit District	20.67	Bi-State Development Agency	13.91	39.064%
Minimum	Massachusetts Bay Transportation Authority	5.58	Metropolitan Transit Authority of Harris County, Texas	3.66	41.547%
Mean	9.49		8.69		8.791%
% Difference Max and Min	114.91%		116.63%		

These ranges have been graphed in Figure 6-22

Figure 6-22 Average Journey Length (km) for Heavy Rail and Light Rail Transit Systems



As indicated by the figures and tables, the HR systems have a balanced performance profile, with representation in each quartile, as do the LR systems. However, LR systems are more represented in the Highest performance categories, indicating better performance for the average trip length factor. In terms of the highest performing systems in each set, Metropolitan Transit Authority of Harris County, a LR system outperforms the HR System, Massachusetts Bay Transportation Authority with a percent difference of 41.547%. For the lowest performing systems, Bi-State Development Agency, a LR system outperforms the HR San Francisco Bay Area Rapid Transit District system with a percent difference of 39.064%. For the system averages, there is a percent difference of 8.791%.

A t test was conducted with a hypothesis that the difference between the means of the systems is greater than zero and a null hypothesis that the difference between the means is zero. The t test returns a value of 0.18546, which is less than 1.9723 indicating that the null hypothesis cannot be rejected at 95% confidence level.

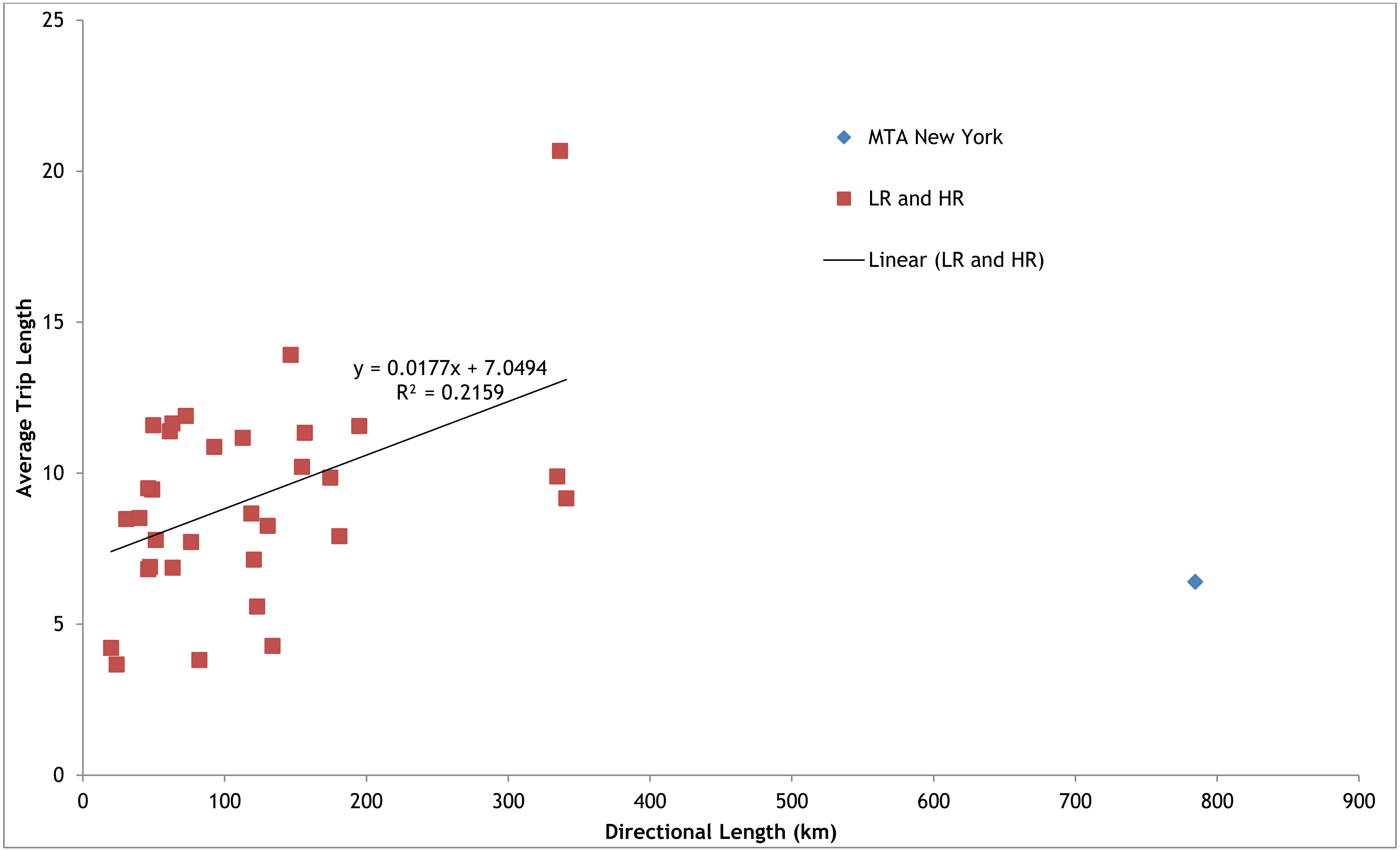
While this factor intends to measure the transit system's ability to provide accessible transit service to its customers, there are other factors to consider which may provide a low score. The NTD dataset provides information on system length. As shorter systems may score greater on this factor than their longer counterparts, an investigation has been conducted in Table 6-40 and Figure 6-23. It is also worth noting that longer systems may also be intended to serve a downtown system and operate as more of a commuter style system as well, which would also reinforce longer trips. As the highest performing system, Metropolitan Transit Authority of Harris County, Texas, is also a short system (23.83433 directional km) that serves a small area of Houston it may be the case that small systems are over represented in this factor. By investigating the influence of system length on average journey length the suitability of this factor can be commented on.

Table 6-40 Directional Route Length and Average Journey Length for Heavy Rail and Light Rail Transit Systems

Mode	Operator Name	Average Journey Length (km)	Directional Route km
LR	Metropolitan Transit Authority of Harris County, Texas	3.664	23.834
LR	Massachusetts Bay Transportation Authority	3.815	82.076
LR	Niagara Frontier Transportation Authority	4.217	19.956
LR	San Francisco Municipal Railway	4.278	133.736
HR	Massachusetts Bay Transportation Authority	5.585	122.793
HR	MTA New York City Transit	6.407	784.553
HR	Port Authority Trans-Hudson Corporation	6.818	46.027
LR	Utah Transit Authority	6.873	63.360
HR	Maryland Transit Administration	6.897	47.315
HR	Southeastern Pennsylvania Transportation Authority	7.134	120.540
LR	Port Authority of Allegheny County	7.723	76.234
HR	Los Angeles County Metropolitan Transportation Authority	7.792	51.338
LR	Tri-County Metropolitan Transportation District of Oregon	7.915	180.825
LR	Santa Clara Valley Transportation Authority	8.253	130.292
LR	Charlotte Area Transit System	8.479	30.513
LR	Metro Transit	8.518	39.815
LR	Sacramento Regional Transit District	8.668	118.737
HR	Washington Metropolitan Area Transit Authority	9.164	340.858
LR	The Greater Cleveland Regional Transit Authority	9.460	48.892
HR	MTA Staten Island Railway	9.501	46.027
LR	San Diego Metropolitan Transit System	9.851	174.453
HR	Chicago Transit Authority	9.896	334.485
HR	Metropolitan Atlanta Rapid Transit Authority	10.211	154.593
LR	Maryland Transit Administration	10.872	92.698
LR	Denver Regional Transportation District	11.169	112.654
LR	Dallas Area Rapid Transit	11.339	156.396
HR	The Greater Cleveland Regional Transit Authority	11.392	61.284

Mode	Operator Name	Average Journey Length (km)	Directional Route km
LR	Los Angeles County Metropolitan Transportation Authority	11.559	194.923
LR	Central Puget Sound Regional Transit Authority	11.585	49.568
LR	Valley Metro Rail, Inc.	11.647	63.054
HR	Miami-Dade Transit	11.894	72.485
LR	Bi-State Development Agency	13.914	146.547
HR	San Francisco Bay Area Rapid Transit District	20.669	336.416

Figure 6-23 Average trip length as a function of directional length for Heavy Rail and Light Rail Transit Systems



As observed in the graph and table, there is a slight trend, however the influence of length on average travel length based on this data set is low, even when the major point outside of the trend, MTA New York, is removed from consideration. Given the low R^2 value here are other factors that need to be considered when analyzing the journey length factor. This test's inquiry does not demonstrate an overwhelming influence by system length on average journey length so this factor will be utilized in the sustainability study. Future research should consider system lengths as well as route length, which could not be considered in this study given the data structure of the NTD set, impact on this factor and its subsequent suitability in research.

The final accessibility factor is based on data obtained from the NTD set that reflects the number of stations/stops in the system that adhere to the requirements set out in the ADA Accessible Stations guidelines. As these guidelines are based on stations, whose ADA compliance is assumed to be independent of mode, the results of the factor generation are shared here with little commentary. As further data, such as the type of station (elevated, underground, age, type of facilities), beyond the number of elevators or escalators, are not available in the NTD dataset, further commentary is not possible with this dataset. All data for this factor is found within the NTD data set – ADA compliant stations and total number of stations in a given mode of the system. The factor is expressed as a percent and is shared in Table 6-41.

Table 6-41 User Accessibility Factor for Heavy Rail and Light Rail Transit Systems

Mode	Operator Name	User Accessibility
HR	Washington Metropolitan Area Transit Authority	100.00%
HR	Maryland Transit Administration	100.00%
HR	Metropolitan Atlanta Rapid Transit Authority	100.00%
HR	Miami-Dade Transit	100.00%
HR	San Francisco Bay Area Rapid Transit District	100.00%
HR	Los Angeles County Metropolitan Transportation Authority	100.00%
LR	Tri-County Metropolitan Transportation District of Oregon	100.00%
LR	Central Puget Sound Regional Transit Authority	100.00%
LR	Niagara Frontier Transportation Authority	100.00%
LR	Port Authority of Allegheny County	100.00%
LR	Maryland Transit Administration	100.00%

Mode	Operator Name	User Accessibility
LR	Charlotte Area Transit System	100.00%
LR	Metro Transit	100.00%
LR	Metropolitan Transit Authority of Harris County, Texas	100.00%
LR	Dallas Area Rapid Transit	100.00%
LR	Bi-State Development Agency	100.00%
LR	Utah Transit Authority	100.00%
LR	Denver Regional Transportation District	100.00%
LR	Santa Clara Valley Transportation Authority	100.00%
LR	San Francisco Municipal Railway	100.00%
LR	San Diego Metropolitan Transit System	100.00%
LR	Los Angeles County Metropolitan Transportation Authority	100.00%
LR	Valley Metro Rail, Inc.	100.00%
LR	Sacramento Regional Transit District	97.92%
HR	Massachusetts Bay Transportation Authority	92.45%
HR	The Greater Cleveland Regional Transit Authority	72.22%
HR	Chicago Transit Authority	62.94%
HR	Port Authority Trans-Hudson Corporation	53.85%
LR	Massachusetts Bay Transportation Authority	48.65%
HR	Southeastern Pennsylvania Transportation Authority	40.00%
LR	The Greater Cleveland Regional Transit Authority	26.47%
HR	MTA Staten Island Railway	21.74%
HR	MTA New York City Transit	18.80%

To summarize and conclude the social factor analysis section it was found that, while there is potential for further research into system performance and influence on system performance across all factors, in general LR Systems offer better performance in the NTD data set for 2 factors (system accessibility, affordability, average journey length). A performance factor could be calculated for each system for 4 factors, however general trends could only be commented on for 3. Health impact factors could not be calculated for this methodology. The results of each factor are summarized in Table 6-42.

Table 6-42 Social Factors Conclusion

	Highest Performance Systems	Lowest Performance Systems	Mean	Trend
System Accessibility	LR Systems achieve better performance, highest performing system is HR.	LR Systems are better represented in this category. Lowest performers attain comparable performance.	LR mean value higher.	N/A
Affordability	LR Systems achieve better performance.	LR System attains better performance.	LR systems attain greater performance.	N/A
Average Journey Length	LR Systems achieve better performance.	LR System attains better performance.	Null hypothesis (difference between means is statistically significant) rejected at 95%.	N/A
User Accessibility	N/A			

Overall results indicate that LR systems tend to attain higher results throughout the factors. However, the highest performing HR systems attain comparable results. For the System Accessibility, the HR systems attain a balanced profile, with 3 systems in the highest performance indicator sets (6 total), and 5 and 2 in the lower two performance sets. LR has balanced performance as well, with 5,6,3, and 6 systems from highest to lowest. In the Affordability factor set, HR systems are represented 3,4,1, and 5 from highest to lowest, while LR systems present a 5, 5, 7, 3 split. This indicates HR is weighted heaviest in the top 2 and lowest category, while LR is weighted heaviest in the middle two categories. In the Average Journey length factor, HR follows a 3,3, 4, 3 distribution through the performance categories – showing a heaviest concentration in the middle two performance quartiles. LR shows a 5,6, 4, 5, distribution, with the largest clustering in the top two performance categories indicating highest performance for LR systems. Overall, while some HR systems offer high levels of performance, the general trend is for LR to offer greater performance in the social set. However, there is a gradient of performance with systems of both types attaining high and low performance regardless of their system type.

6.5.4 System Effectiveness Factors

For this implementation of the PTSMAP framework, two system effectiveness measures have been calculated. These measures utilize data from within the NTD and are only expanded with the same population data utilized to calculate the social system accessibility factor. The first factor, pkm/pkm theoretical is a proxy for capacity utilization or also could be considered as a transport work efficiency factor. This factor utilizes vehicle capacity and mileage data, along with system pkm data from within the NTD dataset and required no expansion to calculate for all 33 systems. A second factor, trips per capita, which was utilized in the calculation of a previous factor, system accessibility, was also calculated for all 33 systems.

The results for all 33 systems for both factors are shown in Table 6-43.

Table 6-43 System Effectiveness Factors for Heavy Rail and Light Rail Transit Systems

	Operator Name	City	pkm/theoretical pkm	Annual trips/capita
HR (HR)	Massachusetts Bay Transportation Authority	Boston	8.63%	34.480
	MTA New York City Transit	New York	16.94%	298.363
	Port Authority Trans-Hudson Corporation	Jersey City	19.11%	9.540
	MTA Staten Island Railway	New York	10.05%	16.230
	Southeastern Pennsylvania Transportation Authority	Philadelphia	20.84%	18.494
	Washington Metropolitan Area Transit Authority	Washington	13.05%	73.033
	Maryland Transit Administration	Baltimore	7.63%	6.436
	Metropolitan Atlanta Rapid Transit Authority	Atlanta	10.80%	3.531
	Miami-Dade Transit	Miami	9.60%	3.531
	The Greater Cleveland Regional Transit Authority	Cleveland	17.75%	2.047
	Chicago Transit Authority	Chicago	21.63%	25.379
	San Francisco Bay Area Rapid Transit District	San Francisco-Oakland-Fremont	14.87%	33.543
	Los Angeles County Metropolitan Transportation Authority	Los Angeles	20.43%	4.063
Light Rail (LR)	Tri-County Metropolitan Transportation District of Oregon	Portland	15.63%	26.816
	Central Puget Sound Regional Transit Authority	Seattle	7.60%	12.867
	Massachusetts Bay Transportation Authority	Boston	13.44%	16.236
	Niagara Frontier Transportation Authority	Buffalo	12.10%	23.786

Operator Name	City	pkm/theoretical pkm	Annual trips/capita
Port Authority of Allegheny County	Pittsburgh	9.66%	3.997
Maryland Transit Administration	Baltimore	9.47%	3.887
Charlotte Area Transit System	Charlotte	8.48%	4.443
The Greater Cleveland Regional Transit Authority	Cleveland	14.36%	1.296
Metro Transit	Minneapolis	12.12%	4.377
Metropolitan Transit Authority of Harris County, Texas	Houston	11.83%	5.057
Dallas Area Rapid Transit	Dallas	12.57%	4.293
Bi-State Development Agency	St. Louis	12.89%	7.619
Utah Transit Authority	Salt Lake City	14.39%	15.097
Denver Regional Transportation District	Denver	9.12%	10.120
Santa Clara Valley Transportation Authority	San Jose	10.54%	6.338
San Francisco Municipal Railway	San Francisco	11.43%	61.345
Sacramento Regional Transit District	Sacramento	8.45%	10.992
San Diego Metropolitan Transit System	San Diego	11.68%	11.393
Los Angeles County Metropolitan Transportation Authority	Los Angeles	23.02%	3.936
Valley Metro Rail, Inc.	Phoenix	14.40%	4.167

The results of the first factor, pkm/theoretical pkm, have been ranked and organized by performance quartiles. These results are shown in Table 6-44.

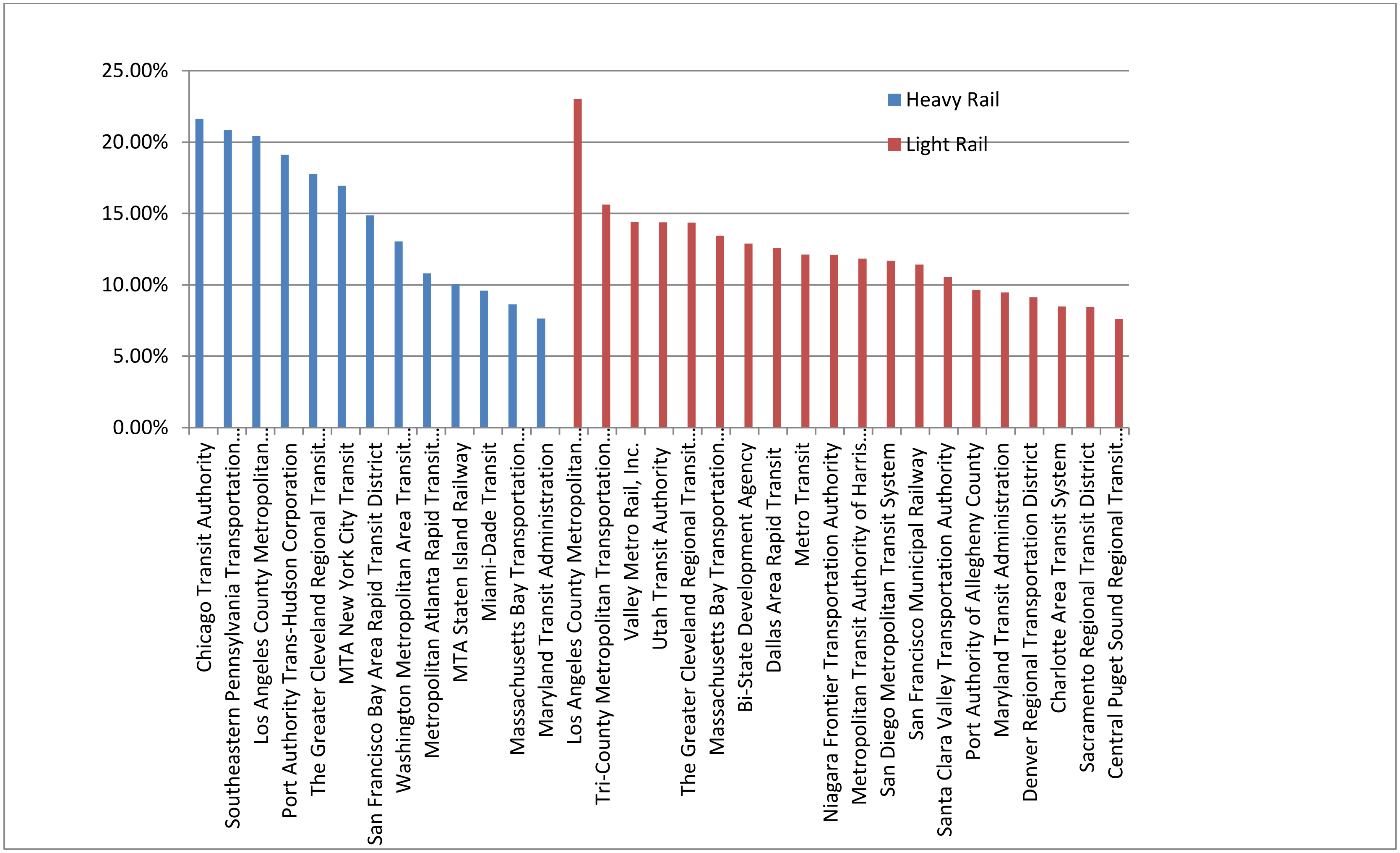
Table 6-44 pkm/pkm theoretical for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	pkm/theoretical pkm	Performance
1	Los Angeles County Metropolitan Transportation Authority	LR	23.02%	Highest
2	Chicago Transit Authority	HR	21.63%	LR
3	Southeastern Pennsylvania Transportation Authority	HR	20.84%	2
4	Los Angeles County Metropolitan Transportation Authority	HR	20.43%	HR
5	Port Authority Trans-Hudson Corporation	HR	19.11%	6
6	The Greater Cleveland Regional Transit Authority	HR	17.75%	
7	MTA New York City Transit	HR	16.94%	
8	Tri-County Metropolitan Transportation District of Oregon	LR	15.63%	
9	San Francisco Bay Area Rapid Transit District	HR	14.86%	High
10	Valley Metro Rail, Inc.	LR	14.40%	LR
11	Utah Transit Authority	LR	14.38%	7
12	The Greater Cleveland Regional Transit Authority	LR	14.37%	HR
13	Massachusetts Bay Transportation Authority	LR	13.44%	2
14	Washington Metropolitan Area Transit Authority	HR	13.05%	
15	Bi-State Development Agency	LR	12.89%	
16	Dallas Area Rapid Transit	LR	12.57%	
17	Metro Transit	LR	12.12%	
18	Niagara Frontier Transportation Authority	LR	12.10%	Low
19	Metropolitan Transit Authority of Harris County, Texas	LR	11.83%	LR
20	San Diego Metropolitan Transit System	LR	11.68%	6
21	San Francisco Municipal Railway	LR	11.43%	HR
22	Metropolitan Atlanta Rapid Transit Authority	HR	10.80%	2
23	Santa Clara Valley Transportation Authority	LR	10.54%	

Rank	Operator Name	Mode	pkm/theoretical pkm	Performance
24	MTA Staten Island Railway	HR	10.05%	
25	Port Authority of Allegheny County	LR	9.66%	
26	Miami-Dade Transit	HR	9.60%	Poorest
27	Maryland Transit Administration	LR	9.47%	LR
28	Denver Regional Transportation District	LR	9.12%	5
29	Massachusetts Bay Transportation Authority	HR	8.62%	HR
30	Charlotte Area Transit System	LR	8.48%	3
31	Sacramento Regional Transit District	LR	8.44%	
32	Maryland Transit Administration	HR	7.63%	
33	Central Puget Sound Regional Transit Authority	LR	7.61%	
System Mean			13.17%	

These results are also graphed in Figure 6-24.

Figure 6-24 pkm/pkm theoretical for Heavy Rail and Light Rail Transit Systems



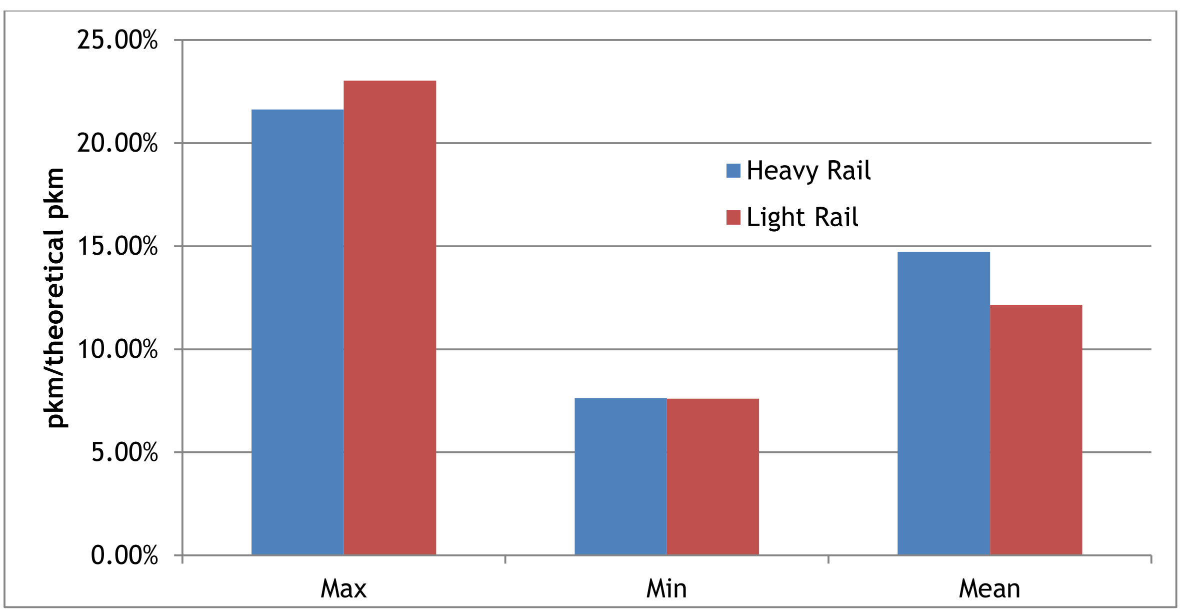
The maximum, minimum, and mean values, along with percent differences within and between system sets have also been calculated. These are shown in Table 6-45.

Table 6-45 pkm/ pkm theoretical ranges for Heavy Rail and Light Rail Transit Systems

	Capacity Utilization				
	HR		LR		% Difference
Maximum	Chicago Transit Authority	21.63%	Los Angeles County Metropolitan Transportation Authority	23.02%	6.222%
Minimum	Maryland Transit Administration	7.63%	Central Puget Sound Regional Transit Authority	7.60%	0.363%
Mean	14.72%		12.16%		19.047%
% Difference Max and Min	95.68%		100.67%		

These values have also been graphed in Figure 6-25.

Figure 6-25 pkm/ pkm theoretical Ranges for Heavy and Light Rail Transit Systems



It can be observed from the tables and figures that, in general, HR systems have achieved better performance for the pkm/pkm theoretical indicator for the systems in the NTD data set. Within the highest performance category, 6 systems were HR systems, while only two were LR. For the second performance tier, LR systems have 7 of 9 slots, and HR systems have 2. While HR systems have the highest performance, LR achieve more balanced performance.

A LR system, Los Angeles County Metropolitan Transportation Authority, achieves the highest performance and there is a percent difference of 6.222% when compared to the top HR system, Chicago Transit Authority. This is a small difference, highlighting how LR and HR systems can both achieve similar levels of performance. There is little difference between the two lowest performing systems. There is a 19.047% difference between the means of the system sets, with HR having a greater mean performance.

This factor is a proxy for the level of efficiency and effectiveness built into the planning of the overall transit system. Systems that score well have planned their operations to offer services commensurate with ridership. A high performing system will use more of its available capacity, while a poorly performing system will use little of its capacity indicating it is over providing service for the amount of ridership it generates. As this indicator is based on the annual pkm it takes into account all potential trips the system can generate with its rolling stock. However, performance level considerations, such as crowding, waiting time, and transfers are not included in this factor so it is a very high level abstraction of performance measurement. As these details are not available within the NTD dataset, follow up investigation is outside of the scope of this implementation of the PTSMAP framework.

The next factor, annual trips/capita, which reflects the system’s ability to generate trips from its population, has been calculated for each system and sorted by performance quartile. These values are shown in Table 6-46.

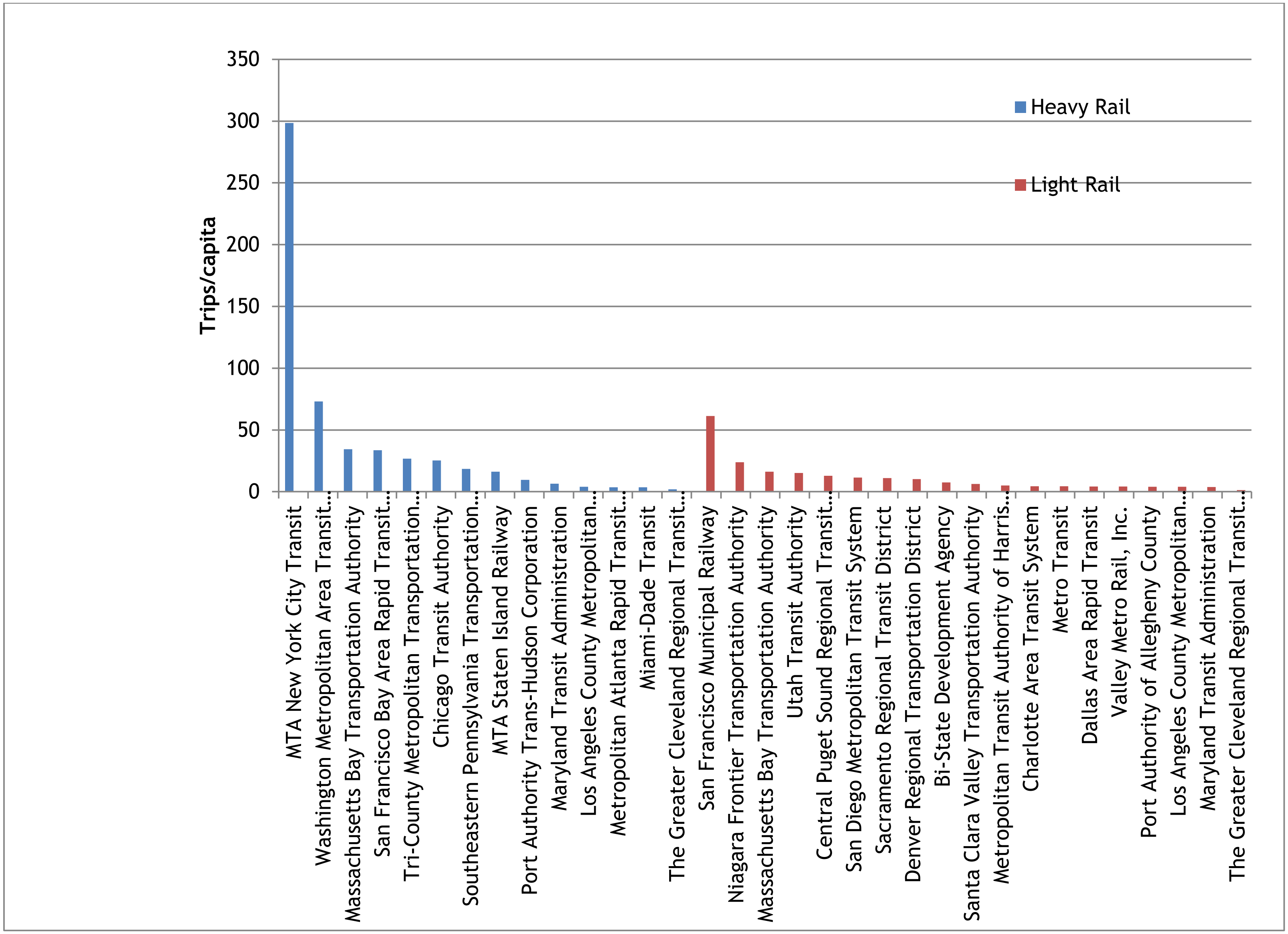
Table 6-46 Annual Trips/Capita for Heavy Rail and Light Rail Transit Systems

Rank	Operator Name	Mode	Annual trips/capita	Performance
1	MTA New York City Transit	HR	298.36	Highest
2	Washington Metropolitan Area Transit Authority	HR	73.03	LR
3	San Francisco Municipal Railway	LR	61.34	3
4	Massachusetts Bay Transportation Authority	HR	34.48	HR
5	San Francisco Bay Area Rapid Transit District	HR	33.54	5
6	Tri-County Metropolitan Transportation District of Oregon	LR	26.82	
7	Chicago Transit Authority	HR	25.38	
8	Niagara Frontier Transportation Authority	LR	23.79	
9	Southeastern Pennsylvania Transportation Authority	HR	18.49	High
10	Massachusetts Bay Transportation Authority	LR	16.24	LR
11	MTA Staten Island Railway	HR	16.23	6
12	Utah Transit Authority	LR	15.10	HR
13	Central Puget Sound Regional Transit Authority	LR	12.87	3
14	San Diego Metropolitan Transit System	LR	11.39	
15	Sacramento Regional Transit District	LR	10.99	
16	Denver Regional Transportation District	LR	10.12	
17	Port Authority Trans-Hudson Corporation	HR	9.54	
18	Bi-State Development Agency	LR	7.62	Low
19	Maryland Transit Administration	HR	6.44	LR
20	Santa Clara Valley Transportation Authority	LR	6.34	7
21	Metropolitan Transit Authority of Harris County, Texas	LR	5.06	HR
22	Charlotte Area Transit System	LR	4.44	1
23	Metro Transit	LR	4.38	
24	Dallas Area Rapid Transit	LR	4.29	
25	Valley Metro Rail, Inc.	LR	4.17	
26	Los Angeles County Metropolitan Transportation Authority	HR	4.06	Poorest
27	Port Authority of Allegheny County	LR	4.00	LR

Rank	Operator Name	Mode	Annual trips/capita	Performance
28	Los Angeles County Metropolitan Transportation Authority	LR	3.94	4
29	Maryland Transit Administration	LR	3.89	HR
30	Miami-Dade Transit	HR	3.53	4
31	Metropolitan Atlanta Rapid Transit Authority	HR	3.53	
32	The Greater Cleveland Regional Transit Authority	HR	2.05	
33	The Greater Cleveland Regional Transit Authority	LR	1.30	
System Mean			23.23	

These values are also shown in Figure 6-26.

Figure 6-26 Trips/Capita for Heavy Rail and Light Rail Transit Systems

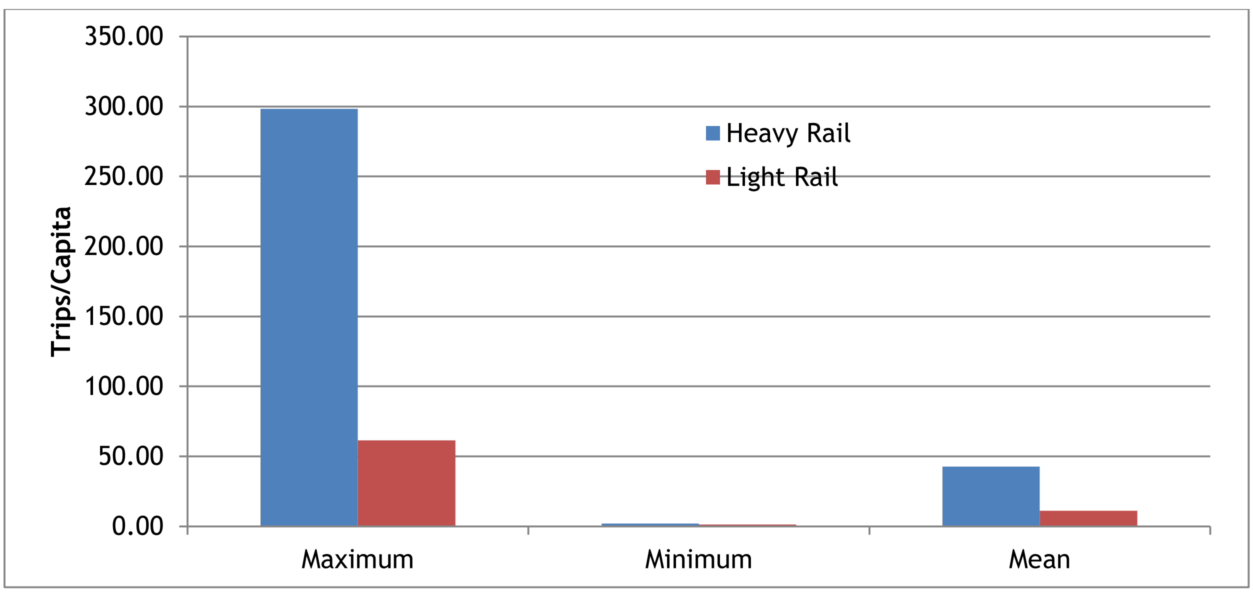


Maximum, minimum, and mean ranges for both system sets have also been calculated. These are displayed in Table 6-47 and Figure 6-27.

Table 6-47 Trips/Capita Ranges for Heavy Rail and Light Rail Transit Systems

	Trips/Capita				
	HR		LR		% Difference
Maximum	MTA New York City Transit	298.36	San Francisco Municipal Railway	61.345	204.713%
Minimum	The Greater Cleveland Regional Transit Authority	2.047	The Greater Cleveland Regional Transit Authority	1.296	129.609%
Mean	42.57		11.118		117.168%
% Difference Max and Min	195.32%		191.72%		

Figure 6-27 Trips/capita Ranges for Heavy Rail and Light Rail Transit Systems



As noted in the tables and figures, HR systems are able to achieve generally better performance than LR systems based on the 5 HR systems in the highest performance category, compared to 3 LR systems in that category. However, there are 6 LR systems in the second highest performance category, compared to 3 HR indicating higher level LR are able to achieve a better level of performance compared to moderate and lower grade HR systems.

The maximum performing HR system, MTA New York City Transit, greatly outperforms the competing LR system, San Francisco Municipal Railway, with a % difference of 204.713%. The lowest performing systems are the same system operator, The Greater Cleveland Regional Transit Authority, and have a difference of 129.609%. HR systems have a greater mean compared to LR, with a percent difference of 117.168%.

The performance breakdown generally favours HR systems, with LR systems achieving superiority in the middle performance tiers. Future research can analyze level of service factors for systems as well as accessibility factors, such as density along transit corridors, as they relate to ridership generation in order to understand which factors shape this performance. As ridership generation is a complex process, further research on the matter is required.

To summarize, both factors ($pkm/pkm_{theoretical}$, and trips/capita) were calculated for both system sets. These effectiveness indicators represent the system’s ability to generate ridership and provide an effective transit service and it was shown that in general HR systems outperform LR systems. However given the high level nature of both factors used, no causal connections could be drawn as to why some systems performed better and others did not. In future studies, with higher resolution data these issues can be explored. The general conclusions are outlined in Table 6-48.

Table 6-48 System Effectiveness Conclusions

	Highest Performance Systems	Lowest Performance Systems	Mean	Trend
pkm/pkm theoretical	HR Systems achieve better performance, highest performing system is LR.	LR Systems are better represented in this category. Lowest performers attain comparable performance.	HR mean value higher.	N/A
Trips/capita	HR systems achieve better performance.	LR Systems are better represented in this category. Lowest performers attain comparable performance.	HR systems attain greater performance.	N/A

HR systems follow a 6,2,2,3 distribution for pkm/pkm theoretical demonstrating the greatest performance out of the two system sets. However, LR systems follow a 2,7,6, 5 distribution and have a greater number of systems in the top two performance tiers (9 compared to 8) indicating that high level LR systems, while not as effective as high performing HR, greatly outperform mid-level HR.

For the trips/capita indicator, HR follows a 5,3,1,4 distribution, again having the greatest performing systems. However, LR also has more systems in the top performance categories (9 compared to 8) and follows a 3,6,7,4 distribution. Again, LR systems in the middle range outperform middle level HR.

6.5.5 PTSMAP Part 2 Conclusion

This research was successful in comparing the performance of LR and HR transit systems based on a complete set of sustainability factors. However, for most of the factors in depth analysis as to where the differing performance levels arise could not be completed given scope and data limitations. As this research is set out to establish a sustainability framework and apply it to determine the differing performance levels for a set of sustainability factors on a modal basis, future research will have to determine the nuance behind each factor.

The overarching conclusion that can be drawn from this analysis is found in the distributions of systems amongst each quartile. As no one indicator was completely populated by one system set for high performance, this research has shown that in general comparable sustainability performance can be achieved by both modes. For some indicators, such as system effectiveness, there is a difference between high HR and high LR, however, in general there is comparable performance between modes with at least one system from each set populating each tier at a comparable level of performance to the opposing system set. This indicates that modal parameters, which often inform the transit debate, may not be as important as other factors when planning and developing a system to meet sustainability criteria. As many factors are normalized by a pkm basis, this research shows that highest performing systems are able to minimize their inputs (i.e. energy, operating costs) and outputs (i.e. emissions) with respect to ridership. Under this framework, comparable performance is observed between high and low end systems. Lower end systems have too high an input for their level of performance. Rather than continue the discussion based strictly on technology, the discussion should be informed on providing the best performance for sustainable mobility, which as demonstrated, the PTSMAP framework is able to provide guidance on. However, it is also noteworthy that no one system attained highest performance in all categories. This reflects the complexity of sustainability – when analyzing transit systems from multiple criteria as opposed to the few criteria in traditional analysis, there are few systems that will achieve top performance across all criteria. These conclusions will be expanded upon with the calculation of composite sustainability and categorical indices in the following section.

6.6 Composite Sustainability Assessment

6.6.1 Application Of Methodology

n the previous section, values for each factor were calculated.. Chapter 7 follows this chapter's analysis of individual factors through the synthesis of factors into categorical indices for environmental, economic, social ,and system effectiveness indices as well as composite sustainability indices for each system. These values will now be used to calculate indices for each category as well as for part 3 of the PTSMAP framework to calculate a CSI index. These indices can be calculated in the following ways:

- Technique 1: z-score
- Technique 2: utility
- Technique 3: Re-scaling

This section of the chapter contains the complete steps for both methodologies including:

- Calculating the inputs for categorical indices
- Calculating the categorical indices
- Calculating the CSI

6.6.2 Methodology 1 z-score

The first step of this methodology is to calculate the four categorical indices. In order to do so, recall equation 3-3:

$$Z = \frac{x - \mu}{\sigma}$$

Z must be calculated for each factor value – larger values indicate a higher rank relative to the mean value, while smaller values indicate a lower rank relative to the mean. Recalling that the score a system achieves is summed up based on the weighting of each factor, or sub factor, in order to develop a categorical index. The results of these calculations are shown in Table 6 49,Table 6-50, Table 6 51, and 6-52 representing each set of factors for each category. Table 6 53 displays the weighting values to be used in index calculation.

Table 6-49 Environmental Index Calculation

		Energy		Emissions/km						
	Operator Name	wH/ pkm	MJ/pkm	CO2	CH4	N2O	CO2E	SO2	Nox	Hg
HR	Massachusetts Bay Transportation Authority	-0.044	-0.044	-0.034	1.704	-0.080	-0.033	-0.226	-0.367	-0.319
HR	MTA New York City Transit	-1.140	-1.140	-0.918	-0.942	-0.815	-0.917	-0.573	-0.738	-0.633
HR	Port Authority Trans-Hudson Corporation	-0.590	-0.590	-0.739	-0.666	-0.668	-0.739	-0.450	-0.636	-0.488
HR	Staten Island Rapid Transit Operating Authority	0.384	0.384	-0.315	0.107	-0.428	-0.316	-0.375	-0.401	-0.364
HR	Southeastern Pennsylvania Transportation Authority	-0.287	-0.287	-0.178	-0.479	-0.018	-0.178	0.316	-0.059	n/a
HR	Washington Metropolitan Area Transit Authority	-0.555	-0.555	0.823	2.851	-0.009	0.819	0.206	0.784	-0.781
HR	Maryland Transit Administration	1.838	1.838	1.429	1.720	1.613	1.430	2.209	1.567	1.595
HR	Metropolitan Atlanta Rapid Transit Authority	-1.061	-1.061	-0.576	-1.049	-0.397	-0.575	-0.162	-0.520	-0.379
HR	Miami-Dade Transit	0.621	0.621	0.464	1.227	0.228	0.464	-0.099	0.561	-0.347
HR	The Greater Cleveland Regional Transit Authority	2.731	2.731	3.216	1.111	3.252	3.216	3.034	3.257	2.862
HR	Chicago Transit Authority	-0.490	-0.490	-0.386	-1.023	-0.218	-0.385	-0.411	-0.407	0.236
HR	San Francisco Bay Area Rapid Transit District	-1.017	-1.017	-0.963	-0.785	-0.905	-0.963	-0.657	-0.817	-0.750
HR	Los Angeles County Metropolitan Transportation Authority	-0.215	-0.215	-0.725	-0.170	-0.803	-0.726	-0.637	-0.729	-0.724
LR	Tri-County Metropolitan Transportation District of Oregon	-0.763	-0.763	-0.986	-0.977	-0.844	-0.986	-0.634	-0.746	-0.711
LR	Central Puget Sound Regional Transit Authority	-0.858	-0.858	-1.095	-1.233	-0.881	-1.094	-0.673	-0.826	-0.663
LR	Massachusetts Bay Transportation Authority	-0.390	-0.390	-0.252	1.126	-0.250	-0.251	-0.308	-0.467	-0.402

Operator Name	Energy		Emissions/km						
	wH/pkm	MJ/pkm	CO2	CH4	N2O	CO2E	SO2	Nox	Hg
Niagara Frontier Transportation Authority	0.711	0.711	-0.186	0.333	-0.344	-0.187	-0.333	-0.329	-0.306
Port Authority of Allegheny County	2.407	2.407	1.530	1.177	1.594	1.530	1.910	1.320	2.653
Maryland Transit Administration	0.947	0.947	0.803	0.963	0.996	0.804	1.533	0.985	1.039
Charlotte Area Transit System	-0.128	-0.128	-0.052	-0.619	0.135	-0.051	0.022	-0.369	0.022
The Greater Cleveland Regional Transit Authority	1.889	1.889	2.417	0.641	2.486	2.417	2.369	2.509	2.210
Metro Transit	-0.505	-0.505	-0.075	0.098	0.184	-0.073	-0.353	0.342	-0.099
Metropolitan Transit Authority of Harris County, Texas	-0.624	-0.624	-0.321	-0.855	-0.427	-0.322	-0.470	-0.594	-0.250
Dallas Area Rapid Transit	0.666	0.666	0.564	-0.224	0.146	0.561	-0.268	-0.280	0.258
Bi-State Development Agency	-0.722	-0.722	-0.077	-0.849	0.077	-0.077	-0.214	-0.073	0.081
Utah Transit Authority	-0.061	-0.061	0.694	-0.364	0.727	0.694	-0.522	0.940	-0.547
Denver Regional Transportation District	-0.405	-0.405	0.239	-0.593	0.221	0.239	-0.432	0.224	-0.368
Santa Clara Valley Transportation Authority	0.136	0.136	-0.621	0.099	-0.759	-0.622	-0.628	-0.691	-0.713
San Francisco Municipal Railway	-0.042	-0.042	-0.674	-0.037	-0.781	-0.674	-0.632	-0.710	-0.719
Sacramento Regional Transit District	0.025	0.025	-0.654	0.014	-0.773	-0.654	-0.630	-0.703	-0.717
San Diego Metropolitan Transit System	-1.000	-1.000	-0.958	-0.772	-0.903	-0.958	-0.657	-0.815	-0.749
Los Angeles County Metropolitan Transportation Authority	-0.615	-0.615	-0.844	-0.476	-0.854	-0.844	-0.647	-0.773	-0.737
Valley Metro Rail, Inc.	-0.845	-0.845	-0.549	-1.055	-0.501	-0.549	-0.609	-0.439	-0.513

Table 6-50 Economic Index Calculation

		System Costs	User Costs		Economic Efficiency	
	Operator Name	op cost/pkm	Average travel time costs	User Costs - fare	Recovery (%)	Funding/Capita
HR	Massachusetts Bay Transportation Authority	-0.150	-1.371	0.179	0.997	-0.177
HR	MTA New York City Transit	-1.049	-1.136	-0.100	2.321	1.827
HR	Port Authority Trans-Hudson Corporation	0.506	-0.986	0.555	0.093	0.644
HR	Staten Island Rapid Transit Operating Authority	0.330	-0.318	-0.404	-0.934	0.422
HR	Southeastern Pennsylvania Transportation Authority	-0.897	-1.016	-0.316	1.067	-0.407
HR	Washington Metropolitan Area Transit Authority	-0.626	-1.027	1.584	1.728	1.161
HR	Maryland Transit Administration	0.776	-1.737	-0.395	-0.744	-0.504
HR	Metropolitan Atlanta Rapid Transit Authority	-1.039	-0.835	-0.635	0.040	0.717
HR	Miami-Dade Transit	-0.279	-0.575	0.001	-0.623	-0.430
HR	The Greater Cleveland Regional Transit Authority	0.580	0.604	0.202	-0.951	-0.674
HR	Chicago Transit Authority	-1.038	0.407	0.258	1.186	0.441
HR	San Francisco Bay Area Rapid Transit District	-1.085	0.823	4.794	2.313	2.770
HR	Los Angeles County Metropolitan Transportation Authority	-0.910	-1.122	-0.696	0.312	-0.832
LR	Tri-County Metropolitan Transportation District of Oregon	-0.539	0.750	-0.368	0.066	0.107
LR	Central Puget Sound Regional Transit Authority	0.155	1.112	0.474	-0.634	-0.709
LR	Massachusetts Bay Transportation Authority	0.690	-0.672	0.089	0.967	-0.610
LR	Niagara Frontier Transportation Authority	2.360	-0.839	-0.712	-0.887	-0.601

Operator Name	System Costs	User Costs		Economic Efficiency	
	op cost/pkm	Average travel time costs	User Costs - fare	Recovery (%)	Funding/Capita
Port Authority of Allegheny County	2.497	0.823	0.245	-1.087	-0.276
Maryland Transit Administration	0.121	0.625	-0.369	-0.965	-0.614
Charlotte Area Transit System	0.783	-0.152	-0.088	-0.829	-0.583
The Greater Cleveland Regional Transit Authority	0.758	1.021	0.202	-0.809	-0.815
Metro Transit	-0.676	0.709	-0.082	0.405	-0.789
Metropolitan Transit Authority of Harris County, Texas	-0.218	-1.491	-1.132	0.332	-0.910
Dallas Area Rapid Transit	0.647	1.369	-0.546	-1.280	-0.014
Bi-State Development Agency	-0.895	0.625	0.117	-0.126	-0.424
Utah Transit Authority	-0.601	-0.056	-0.586	0.217	-0.745
Denver Regional Transportation District	-0.530	1.076	0.191	-0.152	-0.538
Santa Clara Valley Transportation Authority	1.392	0.408	-0.336	-1.124	-0.377
San Francisco Municipal Railway	1.869	-0.067	-0.600	-0.677	2.701
Sacramento Regional Transit District	-0.321	-0.375	-0.194	-0.208	-0.262
San Diego Metropolitan Transit System	-1.104	0.537	0.139	1.258	-0.647
Los Angeles County Metropolitan Transportation Authority	-0.556	0.188	-0.857	-0.934	-0.607
Valley Metro Rail, Inc.	-0.951	2.700	-0.616	-0.338	1.755

Table 6-51 Social Index Calculation

	Operator Name	System Accessibility	Affordability	Average Journey Length	User Accessibility
HR	Massachusetts Bay Transportation Authority	-0.383	-0.315	-1.029	0.249
HR	MTA New York City Transit	3.971	-0.407	-0.782	-2.551
HR	Port Authority Trans-Hudson Corporation	-0.329	0.376	-0.658	-1.219
HR	Staten Island Rapid Transit Operating Authority	-0.124	-0.771	0.149	-2.439
HR	Southeastern Pennsylvania Transportation Authority	0.583	-0.420	-0.563	-1.745
HR	Washington Metropolitan Area Transit Authority	-0.062	0.742	0.048	0.536
HR	Maryland Transit Administration	-0.415	-0.712	-0.634	0.536
HR	Metropolitan Atlanta Rapid Transit Authority	-0.380	-0.491	0.363	0.536
HR	Miami-Dade Transit	-0.433	0.666	0.870	0.536
HR	The Greater Cleveland Regional Transit Authority	-0.435	0.874	0.718	-0.520
HR	Chicago Transit Authority	1.326	0.532	0.268	-0.873
HR	San Francisco Bay Area Rapid Transit District	0.445	4.418	3.510	0.536
HR	Los Angeles County Metropolitan Transportation Authority	-0.446	-0.652	-0.365	0.536
LR	Tri-County Metropolitan Transportation District of Oregon	-0.152	-0.215	-0.328	0.536
LR	Central Puget Sound Regional Transit Authority	-0.188	0.365	0.777	0.536
LR	Massachusetts Bay Transportation Authority	-0.435	-0.413	-1.562	-1.416
LR	Niagara Frontier Transportation Authority	-0.082	-0.489	-1.441	0.536
LR	Port Authority of Allegheny County	-0.434	0.726	-0.386	0.536
LR	Maryland Transit Administration	-0.417	-0.682	0.562	0.536
LR	Charlotte Area Transit System	-0.402	0.291	-0.158	0.536
LR	The Greater Cleveland Regional Transit Authority	-0.446	0.874	0.137	-2.259
LR	Metro Transit	-0.431	-0.232	-0.146	0.536
LR	Metropolitan Transit Authority of Harris County, Texas	-0.454	-1.249	-1.607	0.536

Operator Name	System Accessibility	Affordability	Average Journey Length	User Accessibility
Dallas Area Rapid Transit	-0.436	-0.428	0.702	0.536
Bi-State Development Agency	-0.371	0.515	1.477	0.536
Utah Transit Authority	-0.151	-0.149	-0.642	0.536
Denver Regional Transportation District	-0.304	0.174	0.651	0.536
Santa Clara Valley Transportation Authority	-0.321	-0.955	-0.226	0.536
San Francisco Municipal Railway	3.206	-1.264	-1.422	0.536
Sacramento Regional Transit District	-0.282	0.093	-0.101	0.456
San Diego Metropolitan Transit System	-0.361	0.384	0.255	0.536
Los Angeles County Metropolitan Transportation Authority	-0.441	-0.888	0.769	0.536
Valley Metro Rail, Inc.	-0.418	-0.296	0.795	0.536

6-52 System Effectiveness Index Calculation

	Operator Name	pkm/theoretical pkm	Annual trips/capita
HR	Massachusetts Bay Transportation Authority	-0.922	0.216
HR	MTA New York City Transit	0.638	5.289
HR	Port Authority Trans-Hudson Corporation	1.044	-0.263
HR	Staten Island Rapid Transit Operating Authority	-0.656	-0.135
HR	Southeastern Pennsylvania Transportation Authority	1.369	-0.091
HR	Washington Metropolitan Area Transit Authority	-0.093	0.957
HR	Maryland Transit Administration	-1.109	-0.323
HR	Metropolitan Atlanta Rapid Transit Authority	-0.515	-0.379
HR	Miami-Dade Transit	-0.739	-0.379
HR	The Greater Cleveland Regional Transit Authority	0.789	-0.407
HR	Chicago Transit Authority	1.517	0.041
HR	San Francisco Bay Area Rapid Transit District	0.248	0.198
HR	Los Angeles County Metropolitan Transportation Authority	3.628	-0.369
LR	Tri-County Metropolitan Transportation District of Oregon	0.392	0.069
LR	Central Puget Sound Regional Transit Authority	-1.114	-0.199
LR	Massachusetts Bay Transportation Authority	-0.019	-0.135
LR	Niagara Frontier Transportation Authority	-0.272	0.011
LR	Port Authority of Allegheny County	-0.729	-0.370
LR	Maryland Transit Administration	-0.765	-0.372
LR	Charlotte Area Transit System	-0.951	-0.361
LR	The Greater Cleveland Regional Transit Authority	0.154	-0.422
LR	Metro Transit	-0.267	-0.363
LR	Metropolitan Transit Authority of Harris County, Texas	-0.322	-0.349
LR	Dallas Area Rapid Transit	-0.183	-0.364
LR	Bi-State Development Agency	-0.123	-0.300
LR	Utah Transit Authority	0.158	-0.156
LR	Denver Regional Transportation District	-0.830	-0.252

Operator Name	pkm/theoretical pkm	Annual trips/capita
Santa Clara Valley Transportation Authority	-0.564	-0.325
San Francisco Municipal Railway	-0.397	0.733
Sacramento Regional Transit District	-0.956	-0.235
San Diego Metropolitan Transit System	-0.350	-0.228
Los Angeles County Metropolitan Transportation Authority	1.778	-0.371
Valley Metro Rail, Inc.	0.160	-0.367

Table 6-53 Weighting Factors for Index Calculation

Environmental Factors		**Economic Factors**		**Social Factors**		**System Factors**	
Energy Consumption	0.33	op cost/pkm	0.2	System Accessibility	0.25	Average Capacity	0.5
GHg	0.33	Average travel time costs(minutes)	0.2	Affordability (fare/per capita GDP)	0.25	Trips per capita	0.5
Pollution	0.33	User Costs - fare / unlinked trip $ (USD)	0.2	Average Journey Length (km)	0.25		
SO2	0.33	Recovery (%)	0.2	user accessibility	0.25		
Nox	0.33	PKM/GDP	0.2				
Hg	0.33						

With all the factor z values calculated, the categorical indices can also be calculated based on the weightings in table 6-55. Recalling equation 5-1:

$$I = \sum_{i=1}^{j} w_i f_i$$

For this study, all factors are assigned equal weighting with the sum of all w equalling 1. For the environmental category, there are three pollution sub factors used in this study (SO2, NOx, Hg), so each one is given a weighting value of 1/3 and the overall factor for the category is 1/3 as there are three environmental factors. Using the weights and the factor z values, the indices for each category can be calculated. These results are shown in Table 6-54. EI represents the environmental index, EcI represents the economic index, SI represents the social index, and SeI represents the system effectiveness index.

Table 6-54 Category Indices for Heavy Rail and Light Rail Transit Systems

Operator Name	EI	EcI	SI	SeI
Massachusetts Bay Transportation Authority	0.127	0.528	0.302	-0.353
MTA New York City Transit	0.902	1.773	0.652	2.964
Port Authority Trans-Hudson Corporation	0.618	-0.099	-0.316	0.390
Staten Island Rapid Transit Operating Authority	0.104	-0.242	-0.485	-0.395
Southeastern Pennsylvania Transportation Authority	0.066	0.680	-0.045	0.639
Washington Metropolitan Area Transit Authority	-0.198	0.721	-0.079	0.432
Maryland Transit Administration	-1.686	0.036	0.367	-0.716
Metropolitan Atlanta Rapid Transit Authority	0.663	0.605	0.071	-0.447
Miami-Dade Transit	-0.374	-0.028	-0.358	-0.559
The Greater Cleveland Regional Transit Authority	-2.999	-0.573	-0.637	0.191
Chicago Transit Authority	0.356	0.492	-0.087	0.779
San Francisco Bay Area Rapid Transit District	0.907	-0.031	-	0.223

Operator Name	EI	EcI	SI	SeI
			1.737	
Los Angeles County Metropolitan Transportation Authority	0.546	0.510	0.277	1.630
Tri-County Metropolitan Transportation District of Oregon	0.815	0.107	0.232	0.230
Central Puget Sound Regional Transit Authority	0.891	-0.582	-0.198	-0.657
Massachusetts Bay Transportation Authority	0.345	0.098	0.031	-0.077
Niagara Frontier Transportation Authority	-0.067	-0.430	0.596	-0.131
Port Authority of Allegheny County	-1.966	-1.030	-0.060	-0.549
Maryland Transit Administration	-0.979	-0.357	0.060	-0.568
Charlotte Area Transit System	0.096	-0.393	0.000	-0.656
The Greater Cleveland Regional Transit Authority	-2.223	-0.679	-0.929	-0.134
Metro Transit	0.205	-0.011	0.121	-0.315
Metropolitan Transit Authority of Harris County, Texas	0.461	0.505	0.734	-0.336
Dallas Area Rapid Transit	-0.377	-0.646	-0.044	-0.274
Bi-State Development Agency	0.289	0.006	-0.457	-0.212
Utah Transit Authority	-0.197	0.265	0.294	0.001
Denver Regional Transportation District	0.119	-0.203	-0.148	-0.541
Santa Clara Valley Transportation Authority	0.388	-0.621	0.349	-0.444
San Francisco Municipal Railway	0.468	-0.462	1.607	0.168
Sacramento Regional Transit District	0.438	0.114	0.046	-0.596
San Diego Metropolitan Transit System	0.900	0.340	-0.116	-0.289
Los Angeles County Metropolitan Transportation Authority	0.726	-0.022	0.054	0.703
Valley Metro Rail, Inc.	0.638	-0.373	-0.095	-0.103

With these indices calculated for each system, the composite sustainability index values for the 33 systems can be calculated. Recalling equation 5-2:

$$CSI_q = w_e \sum_{i=1}^{L} w_i E_{i,q} + w_s \sum_{i=1}^{M} w_i S_{i,q} + w_n \sum_{i=1}^{N} w_i N_{i,q} + w_y \sum_{i=1}^{O} w_i Y_{i,q}$$

The category weights used for this methodology are listed in Table 6-55.

Table 6-55 Category Index Weights

Index	Weights
EI	0.25
EcI	0.25
SI	0.25
SeI	0.25

Based on these weights, the CSI values for each system have been calculated. These values are displayed in Table 6-56.

Table 6-56 CSI Values for Heavy and Light Rail Systems

	Operator Name	CSI
HR	MTA New York City Transit	1.573
HR	Los Angeles County Metropolitan Transportation Authority	0.741
HR	Chicago Transit Authority	0.385
HR	Southeastern Pennsylvania Transportation Authority	0.335
HR	Metropolitan Atlanta Rapid Transit Authority	0.223
HR	Washington Metropolitan Area Transit Authority	0.219
HR	Massachusetts Bay Transportation Authority	0.151
HR	Port Authority Trans-Hudson Corporation	0.148
HR	San Francisco Bay Area Rapid Transit District	-0.159
HR	Staten Island Rapid Transit Operating Authority,	-0.255
HR	Miami-Dade Transit	-0.33
HR	Maryland Transit Administration	-0.5
HR	The Greater Cleveland Regional Transit Authority	-1.005
LR	San Francisco Municipal Railway	0.445
LR	Los Angeles County Metropolitan Transportation Authority	0.365
LR	Tri-County Metropolitan Transportation District of Oregon	0.346
LR	Metropolitan Transit Authority of Harris County, Texas	0.341
LR	San Diego Metropolitan Transit System	0.209
LR	Massachusetts Bay Transportation Authority	0.099
LR	Utah Transit Authority	0.091
LR	Valley Metro Rail, Inc.	0.017
LR	Metro Transit	0.0004
LR	Sacramento Regional Transit District	0.00001
LR	Niagara Frontier Transportation Authority	-0.008
LR	Santa Clara Valley Transportation Authority	-0.082
LR	Bi-State Development Agency	-0.093
LR	Central Puget Sound Regional Transit Authority	-0.136
LR	Denver Regional Transportation District	-0.193
LR	Charlotte Area Transit System	-0.238
LR	Dallas Area Rapid Transit	-0.335
LR	Maryland Transit Administration	-0.461
LR	Port Authority of Allegheny County	-0.901
LR	The Greater Cleveland Regional Transit Authority	-0.991

6.6.3 Methodology 2: Utility

The first step is to calculate the utility values for each factor. This calculation compares each systems factor value to the highest performing system. Recall equations 5-4 and 5-5:

- For factors that are positive impacts:

$$n_i = \frac{x_i}{Max\ (all\ x)}$$

- For factors that are negative impacts:

$$n_i = \frac{Min\ (all\ x)}{x_i}$$

Where n is the utility value for each factor. As n tends towards 1 it indicated higher performance by the system, while lower values of n indicate poorer performance. The utility values for each factor are shown in Table 6-57, Table 6-58, Table 6-59, and Table 6 60.

Table 6-57 Environment Utility Calculations

	Operator Name	wH/pkm	MJ/pkm	CO2	CH4	N2O	CO2E	SO2	Nox	Hg
HR	Massachusetts Bay Transportation Authority	0.4319	0.4319	0.1250	0.0878	0.1280	0.1251	0.0192	0.1735	0.0665
HR	MTA New York City Transit	1.0000	1.0000	0.4607	0.4928	0.5722	0.4615	0.0809	0.5230	0.2084
HR	Port Authority Trans-Hudson Corporation	0.6024	0.6024	0.2985	0.3324	0.3382	0.2990	0.0378	0.3363	0.1047
HR	Staten Island Rapid Transit Operating Authority	0.3534	0.3534	0.1628	0.1741	0.2022	0.1631	0.0286	0.1848	0.0737
HR	Southeastern Pennsylvania Transportation Authority	0.4941	0.4941	0.1419	0.2727	0.1200	0.1420	0.0088	0.1115	0.0232
HR	Washington Metropolitan Area Transit Authority	0.5873	0.5873	0.0733	0.0647	0.1190	0.0734	0.0099	0.0564	-
HR	Maryland Transit Administration	0.2185	0.2185	0.0567	0.0874	0.0459	0.0567	0.0030	0.0387	0.0129
HR	Metropolitan Atlanta Rapid Transit Authority	0.9137	0.9137	0.2259	0.6056	0.1923	0.2261	0.0169	0.2395	0.0765
HR	Miami-Dade Transit	0.3211	0.3211	0.0886	0.1031	0.0965	0.0887	0.0150	0.0649	0.0708
HR	The Greater Cleveland Regional Transit Authority	0.1771	0.1771	0.0340	0.1076	0.0283	0.0340	0.0024	0.0230	0.0084
HR	Chicago Transit Authority	0.5617	0.5617	0.1761	0.5734	0.1497	0.1762	0.0323	0.1869	0.0302
HR	San Francisco Bay Area Rapid Transit District	0.8721	0.8721	0.5348	0.3866	1.0000	0.5361	0.3566	0.9189	1.0000
HR	Los Angeles County Metropolitan Transportation Authority	0.4739	0.4739	0.2906	0.2101	0.5434	0.2914	0.1938	0.4993	0.5434
LR	Tri-County Metropolitan Transportation District of Oregon	0.6886	0.6886	0.5818	0.5248	0.6644	0.5826	0.1818	0.5475	0.4387
LR	Central Puget Sound Regional Transit Authority	0.7472	0.7472	1.0000	1.0000	0.8368	1.0000	1.0000	1.0000	0.2596
LR	Massachusetts Bay Transportation Authority	0.5264	0.5264	0.1524	0.1070	0.1560	0.1525	0.0235	0.2114	0.0810

Operator Name	wH/pkm	MJ/pkm	CO2	CH4	N2O	CO2E	SO2	Nox	Hg
Niagara Frontier Transportation Authority	0.3103	0.3103	0.1429	0.1529	0.1775	0.1432	0.0251	0.1623	0.0647
Port Authority of Allegheny County	0.1902	0.1902	0.0546	0.1050	0.0462	0.0546	0.0034	0.0429	0.0089
Maryland Transit Administration	0.2852	0.2852	0.0740	0.1140	0.0599	0.0740	0.0040	0.0505	0.0169
Charlotte Area Transit System	0.4514	0.4514	0.1269	0.3151	0.1042	0.1269	0.0125	0.1740	0.0382
The Greater Cleveland Regional Transit Authority	0.2157	0.2157	0.0414	0.1311	0.0345	0.0414	0.0029	0.0281	0.0103
Metro Transit	0.5677	0.5677	0.1294	0.1752	0.1000	0.1293	0.0267	0.0761	0.0450
Metropolitan Transit Authority of Harris County, Texas	0.6174	0.6174	0.1638	0.4280	0.2021	0.1642	0.0415	0.2934	0.0578
Dallas Area Rapid Transit	0.3156	0.3156	0.0837	0.2188	0.1033	0.0839	0.0212	0.1500	0.0295
Bi-State Development Agency	0.6659	0.6659	0.1296	0.4240	0.1097	0.1297	0.0187	0.1134	0.0356
Utah Transit Authority	0.4358	0.4358	0.0781	0.2454	0.0690	0.0782	0.0550	0.0517	0.1315
Denver Regional Transportation District	0.5314	0.5314	0.1020	0.3063	0.0970	0.1021	0.0351	0.0840	0.0743
Santa Clara Valley Transportation Authority	0.3950	0.3950	0.2422	0.1751	0.4530	0.2428	0.1615	0.4162	0.4530
San Francisco Municipal Railway	0.4313	0.4313	0.2645	0.1912	0.4946	0.2652	0.1764	0.4544	0.4946
Sacramento Regional Transit District	0.4170	0.4170	0.2557	0.1848	0.4782	0.2564	0.1705	0.4394	0.4782
San Diego Metropolitan Transit System	0.8568	0.8568	0.5254	0.3798	0.9825	0.5267	0.3504	0.9027	0.9825
Los Angeles County Metropolitan Transportation Authority	0.6135	0.6135	0.3762	0.2719	0.7035	0.3772	0.2509	0.6464	0.7035
Valley Metro Rail, Inc.	0.7385	0.7385	0.2173	0.6139	0.2305	0.2177	0.1210	0.1994	0.1145

Table 6-58 Economic Utility Calculations

	Operator Name	Operating costs	Average travel time	User Costs - fare	Recovery (%)	PKM/GDP
HR	Massachusetts Bay Transportation Authority	0.514	0.867	0.495	0.697	0.200
	MTA New York City Transit	0.948	0.799	0.554	1.000	1.000
	Port Authority Trans-Hudson Corporation	0.385	0.761	0.432	0.490	0.036
	Staten Island Rapid Transit Operating Authority	0.413	0.628	0.638	0.255	0.005
	Southeastern Pennsylvania Transportation Authority	0.830	0.769	0.611	0.713	0.160
	Washington Metropolitan Area Transit Authority	0.679	0.771	0.321	0.864	0.505
	Maryland Transit Administration	0.349	1.000	0.635	0.299	0.052
	Metropolitan Atlanta Rapid Transit Authority	0.939	0.726	0.721	0.478	0.236
	Miami-Dade Transit	0.550	0.673	0.531	0.326	0.065
	The Greater Cleveland Regional Transit Authority	0.375	0.505	0.490	0.251	0.032
	Chicago Transit Authority	0.939	0.527	0.480	0.740	0.322
	San Francisco Bay Area Rapid Transit District	0.981	0.483	0.178	0.998	0.556
	Los Angeles County Metropolitan Transportation Authority	0.839	0.795	0.747	0.540	0.041
LR	Tri-County Metropolitan Transportation District of Oregon	0.641	0.490	0.627	0.484	0.203
	Central Puget Sound Regional Transit Authority	0.445	0.456	0.444	0.324	0.032
	Massachusetts Bay Transportation Authority	0.360	0.692	0.513	0.690	0.064
	Niagara Frontier Transportation Authority	0.226	0.727	0.753	0.266	0.048
	Port Authority of Allegheny County	0.219	0.483	0.483	0.220	0.039
	Maryland Transit Administration	0.452	0.503	0.627	0.248	0.050
	Charlotte Area Transit System	0.349	0.602	0.552	0.279	0.020

Operator Name	Operating costs	Average travel time	User Costs - fare	Recovery (%)	PKM/GDP
The Greater Cleveland Regional Transit Authority	0.352	0.464	0.490	0.284	0.017
Metro Transit	0.702	0.494	0.550	0.562	0.036
Metropolitan Transit Authority of Harris County, Texas	0.533	0.907	1.000	0.545	0.008
Dallas Area Rapid Transit	0.366	0.435	0.687	0.176	0.043
Bi-State Development Agency	0.829	0.503	0.507	0.440	0.140
Utah Transit Authority	0.667	0.587	0.702	0.519	0.112
Denver Regional Transportation District	0.637	0.460	0.493	0.434	0.114
Santa Clara Valley Transportation Authority	0.288	0.527	0.617	0.212	0.035
San Francisco Municipal Railway	0.254	0.589	0.707	0.314	0.053
Sacramento Regional Transit District	0.563	0.637	0.578	0.421	0.117
San Diego Metropolitan Transit System	1.000	0.513	0.503	0.757	0.142
Los Angeles County Metropolitan Transportation Authority	0.648	0.554	0.823	0.255	0.059
Valley Metro Rail, Inc.	0.869	0.350	0.713	0.392	0.060

Table 6-59 Social Utility Calculations

	Operator Name	Affordability	Average Journey Length	System Accessibility	User Accessibility
HR	Massachusetts Bay Transportation Authority	0.668	0.656	0.017	0.925
	MTA New York City Transit	0.691	0.572	1.000	0.188
	Port Authority Trans-Hudson Corporation	0.539	0.537	0.029	0.538
	Staten Island Rapid Transit Operating Authority	0.795	0.386	0.076	0.217
	Southeastern Pennsylvania Transportation Authority	0.694	0.514	0.235	0.400
	Washington Metropolitan Area Transit Authority	0.488	0.400	0.090	1.000
	Maryland Transit Administration	0.776	0.531	0.010	1.000
	Metropolitan Atlanta Rapid Transit Authority	0.712	0.359	0.018	1.000
	Miami-Dade Transit	0.498	0.308	0.006	1.000
	The Greater Cleveland Regional Transit Authority	0.472	0.322	0.006	0.722
	Chicago Transit Authority	0.516	0.370	0.403	0.629
	San Francisco Bay Area Rapid Transit District	0.252	0.177	0.204	1.000
	Los Angeles County Metropolitan Transportation Authority	0.758	0.470	0.003	1.000
LR	Tri-County Metropolitan Transportation District of Oregon	0.646	0.463	0.069	1.000
	Central Puget Sound Regional Transit Authority	0.540	0.316	0.061	1.000
	Massachusetts Bay Transportation Authority	0.692	0.960	0.006	0.486
	Niagara Frontier Transportation Authority	0.712	0.869	0.085	1.000
	Port Authority of Allegheny County	0.490	0.474	0.006	1.000
	Maryland Transit Administration	0.767	0.337	0.010	1.000
	Charlotte Area Transit System	0.552	0.432	0.013	1.000
	The Greater Cleveland Regional Transit Authority	0.472	0.387	0.003	0.265
	Metro Transit	0.650	0.430	0.006	1.000
	Metropolitan Transit Authority of Harris County,	0.992	1.000	0.001	1.000

Operator Name	Affordability	Average Journey Length	System Accessibility	User Accessibility
Texas				
Dallas Area Rapid Transit	0.696	0.323	0.005	1.000
Bi-State Development Agency	0.518	0.263	0.020	1.000
Utah Transit Authority	0.632	0.533	0.070	1.000
Denver Regional Transportation District	0.571	0.328	0.035	1.000
Santa Clara Valley Transportation Authority	0.861	0.444	0.031	1.000
San Francisco Municipal Railway	1.000	0.856	0.827	1.000
Sacramento Regional Transit District	0.585	0.423	0.040	0.979
San Diego Metropolitan Transit System	0.537	0.372	0.022	1.000
Los Angeles County Metropolitan Transportation Authority	0.836	0.317	0.004	1.000
Valley Metro Rail, Inc.	0.664	0.315	0.009	1.000

Table 6-60 System Effectiveness Utility Calculations

	Operator Name	pkm/theoretical pkm	Annual trips/capita
HR	Massachusetts Bay Transportation Authority	0.262	0.116
HR	MTA New York City Transit	0.515	1.000
HR	Port Authority Trans-Hudson Corporation	0.581	0.032
HR	Staten Island Rapid Transit Operating Authority	0.306	0.054
HR	Southeastern Pennsylvania Transportation Authority	0.634	0.062
HR	Washington Metropolitan Area Transit Authority	0.397	0.245
HR	Maryland Transit Administration	0.232	0.022
HR	Metropolitan Atlanta Rapid Transit Authority	0.328	0.012
HR	Miami-Dade Transit	0.292	0.012
HR	The Greater Cleveland Regional Transit Authority	0.540	0.007
HR	Chicago Transit Authority	0.658	0.085
HR	San Francisco Bay Area Rapid Transit District	0.452	0.112
HR	Los Angeles County Metropolitan Transportation Authority	1.000	0.014
LR	Tri-County Metropolitan Transportation District of Oregon	0.475	0.090
LR	Central Puget Sound Regional Transit Authority	0.231	0.043
LR	Massachusetts Bay Transportation Authority	0.409	0.054
LR	Niagara Frontier Transportation Authority	0.368	0.080
LR	Port Authority of Allegheny County	0.294	0.013
LR	Maryland Transit Administration	0.288	0.013
LR	Charlotte Area Transit System	0.258	0.015
LR	The Greater Cleveland Regional Transit Authority	0.437	0.004
LR	Metro Transit	0.369	0.015
LR	Metropolitan Transit Authority of Harris County, Texas	0.360	0.017
LR	Dallas Area Rapid Transit	0.382	0.014
LR	Bi-State Development Agency	0.392	0.026
LR	Utah Transit Authority	0.438	0.051
LR	Denver Regional Transportation District	0.277	0.034
LR	Santa Clara Valley Transportation Authority	0.320	0.021
LR	San Francisco Municipal Railway	0.347	0.206
LR	Sacramento Regional Transit District	0.257	0.037

Operator Name	pkm/theoretical pkm	Annual trips/capita
San Diego Metropolitan Transit System	0.355	0.038
Los Angeles County Metropolitan Transportation Authority	0.700	0.013
Valley Metro Rail, Inc.	0.438	0.014

With all factor utility values calculated the category indices for each system can be calculated. The same formulation and weights used in method 1 are utilized in method 2. The indices are shown in Table 6-61.

Table 6-61 Category Indices for Heavy Rail and Light Rail Transit Systems

	Operator Name	EI	EcI	SI	SeI
HR	Massachusetts Bay Transportation Authority	0.214	0.555	0.567	0.189
	MTA New York City Transit	0.577	0.860	0.613	0.758
	Port Authority Trans-Hudson Corporation	0.354	0.421	0.411	0.307
	Staten Island Rapid Transit Operating Authority	0.204	0.388	0.368	0.180
	Southeastern Pennsylvania Transportation Authority	0.228	0.617	0.461	0.348
	Washington Metropolitan Area Transit Authority	0.228	0.628	0.494	0.321
	Maryland Transit Administration	0.098	0.467	0.579	0.127
	Metropolitan Atlanta Rapid Transit Authority	0.417	0.620	0.522	0.170
	Miami-Dade Transit	0.153	0.429	0.453	0.152
	The Greater Cleveland Regional Transit Authority	0.074	0.331	0.380	0.273
	Chicago Transit Authority	0.274	0.602	0.480	0.371
	San Francisco Bay Area Rapid Transit District	0.722	0.639	0.408	0.282
	Los Angeles County Metropolitan Transportation Authority	0.392	0.592	0.558	0.507
LR	Tri-County Metropolitan Transportation District of Oregon	0.553	0.489	0.545	0.283
	Central Puget Sound Regional Transit Authority	0.833	0.340	0.479	0.137
	Massachusetts Bay Transportation Authority	0.261	0.464	0.536	0.232
	Niagara Frontier Transportation Authority	0.179	0.404	0.666	0.224
	Port Authority of Allegheny County	0.088	0.289	0.493	0.154
	Maryland Transit Administration	0.128	0.376	0.528	0.150
	Charlotte Area Transit System	0.218	0.360	0.499	0.136
	The Greater Cleveland Regional Transit Authority	0.090	0.322	0.282	0.221
	Metro Transit	0.249	0.469	0.522	0.192
	Metropolitan Transit Authority of Harris County, Texas	0.304	0.598	0.748	0.188
	Dallas Area Rapid Transit	0.155	0.341	0.506	0.198
	Bi-State Development Agency	0.284	0.484	0.450	0.209
	Utah Transit Authority	0.198	0.517	0.559	0.244
	Denver Regional Transportation District	0.233	0.428	0.484	0.156
	Santa Clara Valley Transportation Authority	0.327	0.336	0.584	0.171
	San Francisco Municipal Railway	0.357	0.383	0.921	0.277
	Sacramento Regional Transit District	0.345	0.463	0.507	0.147
	San Diego Metropolitan Transit System	0.710	0.583	0.483	0.197
	Los Angeles County Metropolitan Transportation Authority	0.508	0.468	0.539	0.357
	Valley Metro Rail, Inc.	0.367	0.477	0.497	0.226

With the category indices calculated, finally the CSI values can be calculated for each system. The CSI values are shown in Table 6-62.

Table 6-62 CSI Values for Method 2

	Operator Name	CSI
HR	MTA New York City Transit	0.702
	San Francisco Bay Area Rapid Transit District	0.513
	Los Angeles County Metropolitan Transportation Authority	0.512
	Metropolitan Atlanta Rapid Transit Authority	0.432
	Chicago Transit Authority	0.432
	Washington Metropolitan Area Transit Authority	0.418
	Southeastern Pennsylvania Transportation Authority	0.413
	Massachusetts Bay Transportation Authority	0.381
	Port Authority Trans-Hudson Corporation	0.373
	Maryland Transit Administration	0.318
	Miami-Dade Transit	0.297
	Staten Island Rapid Transit Operating Authority	0.285
	The Greater Cleveland Regional Transit Authority	0.265
LR	San Diego Metropolitan Transit System	0.493
	San Francisco Municipal Railway	0.484
	Los Angeles County Metropolitan Transportation Authority	0.468
	Tri-County Metropolitan Transportation District of Oregon	0.467
	Metropolitan Transit Authority of Harris County, Texas	0.46
	Central Puget Sound Regional Transit Authority	0.448
	Valley Metro Rail, Inc.	0.392
	Utah Transit Authority	0.379
	Massachusetts Bay Transportation Authority	0.373
	Niagara Frontier Transportation Authority	0.368
	Sacramento Regional Transit District	0.366
	Metro Transit	0.358
	Bi-State Development Agency	0.357
	Santa Clara Valley Transportation Authority	0.354
	Denver Regional Transportation District	0.325
	Charlotte Area Transit System	0.303
	Dallas Area Rapid Transit	0.3
	Maryland Transit Administration	0.296
	Port Authority of Allegheny County	0.256
	The Greater Cleveland Regional Transit Authority	0.229

6.6.4 Method 3: Re-Scaling

The first step is to re-scale all values based on equation 5-6:

$$n_i = \frac{x_i - \min(all\ x)}{\max(all\ x) - \min(all\ x)}$$

The min value is assigned to the 'loser' – the system with the lowest performance, while the max value is assigned to the 'winner' – the system with the highest performance. Tables 6-63 to 6-66 show the rescaled values across all categories.

Table 6-63 Environmental Rescaling Calculations

	Operator Name	wH/pkm	MJ/pkm	CO2	CH4	N2O	CO2E	SO2	Nox	Hg
Heavy Rail Systems	Massachusetts Bay Transportation Authority	0.717	0.717	0.754	0.281	0.802	0.754	0.879	0.888	0.881
	MTA New York City Transit	1.000	1.000	0.959	0.929	0.978	0.959	0.973	0.978	0.968
	Port Authority Trans-Hudson Corporation	0.858	0.858	0.917	0.861	0.943	0.917	0.940	0.953	0.927
	Staten Island Rapid Transit Operating Authority	0.606	0.606	0.819	0.672	0.885	0.819	0.920	0.896	0.893
	Southeastern Pennsylvania Transportation Authority	0.780	0.780	0.787	0.815	0.787	0.787	0.733	0.812	0.643
	Washington Metropolitan Area Transit Authority	0.849	0.849	0.555	0.000	0.785	0.556	0.763	0.606	
	Maryland Transit Administration	0.231	0.231	0.415	0.277	0.394	0.414	0.223	0.414	0.351
	Metropolitan Atlanta Rapid Transit Authority	0.980	0.980	0.880	0.955	0.878	0.880	0.862	0.925	0.897
	Miami-Dade Transit	0.545	0.545	0.638	0.398	0.727	0.639	0.845	0.660	0.889
	The Greater Cleveland Regional Transit Authority	0.000	0.000	0.000	0.426	0.000	0.000	0.000	0.000	0.000
	Chicago Transit Authority	0.832	0.832	0.835	0.948	0.835	0.835	0.929	0.897	0.727
	San Francisco Bay Area Rapid Transit District	0.968	0.968	0.969	0.890	1.000	0.970	0.996	0.998	1.000
	Los Angeles County Metropolitan Transportation Authority	0.761	0.761	0.914	0.740	0.976	0.914	0.990	0.976	0.993
Light Rail Systems	Tri-County Metropolitan Transportation District of Oregon	0.903	0.903	0.975	0.937	0.985	0.975	0.989	0.981	0.989
	Central Puget Sound Regional Transit Authority	0.927	0.927	1.000	1.000	0.994	1.000	1.000	1.000	0.976
	Massachusetts Bay Transportation Authority	0.806	0.806	0.804	0.422	0.842	0.804	0.902	0.912	0.904
	Niagara Frontier Transportation Authority	0.522	0.522	0.789	0.617	0.865	0.789	0.908	0.878	0.877

Operator Name	wH/pkm	MJ/pkm	CO2	CH4	N2O	CO2E	SO2	Nox	Hg
Port Authority of Allegheny County	0.084	0.084	0.391	0.410	0.399	0.391	0.303	0.474	0.058
Maryland Transit Administration	0.461	0.461	0.560	0.462	0.543	0.560	0.405	0.556	0.505
Charlotte Area Transit System	0.739	0.739	0.758	0.850	0.750	0.758	0.813	0.888	0.786
The Greater Cleveland Regional Transit Authority	0.218	0.218	0.185	0.541	0.184	0.185	0.179	0.183	0.181
Metro Transit	0.836	0.836	0.763	0.674	0.738	0.763	0.914	0.714	0.820
Metropolitan Transit Authority of Harris County, Texas	0.867	0.867	0.820	0.907	0.885	0.821	0.945	0.943	0.861
Dallas Area Rapid Transit	0.533	0.533	0.615	0.753	0.747	0.616	0.891	0.866	0.721
Bi-State Development Agency	0.892	0.892	0.764	0.906	0.764	0.764	0.876	0.816	0.770
Utah Transit Authority	0.721	0.721	0.585	0.787	0.607	0.585	0.959	0.568	0.944
Denver Regional Transportation District	0.810	0.810	0.690	0.843	0.729	0.691	0.935	0.743	0.894
Santa Clara Valley Transportation Authority	0.670	0.670	0.890	0.674	0.965	0.890	0.988	0.967	0.990
San Francisco Municipal Railway	0.716	0.716	0.902	0.707	0.970	0.902	0.989	0.972	0.991
Sacramento Regional Transit District	0.699	0.699	0.898	0.695	0.968	0.898	0.988	0.970	0.991
San Diego Metropolitan Transit System	0.964	0.964	0.968	0.887	0.999	0.968	0.996	0.997	1.000
Los Angeles County Metropolitan Transportation Authority	0.864	0.864	0.942	0.815	0.988	0.942	0.993	0.987	0.996
Valley Metro Rail, Inc.	0.924	0.924	0.873	0.956	0.903	0.874	0.983	0.905	0.934

Table 6-64 Economic Rescaling Calculations

	Operator Name	op cost/pkm	Average travel time costs(minutes)	User Costs - fare / unlinked trip $ (USD)	Recovery (%)	PKM/GDP
Heavy Rail Systems	Massachusetts Bay Transportation Authority	0.948	0.799	0.554	1.000	1.000
	MTA New York City Transit	0.981	0.483	0.178	0.998	0.556
	Port Authority Trans-Hudson Corporation	0.839	0.795	0.747	0.540	0.041
	Staten Island Rapid Transit Operating Authority	1.000	0.513	0.503	0.757	0.142
	Southeastern Pennsylvania Transportation Authority	0.254	0.589	0.707	0.314	0.053
	Washington Metropolitan Area Transit Authority	0.648	0.554	0.823	0.255	0.059
	Maryland Transit Administration	0.641	0.490	0.627	0.484	0.203
	Metropolitan Atlanta Rapid Transit Authority	0.533	0.907	1.000	0.545	0.008
	Miami-Dade Transit	0.445	0.456	0.444	0.324	0.032
	The Greater Cleveland Regional Transit Authority	0.939	0.726	0.721	0.478	0.236
	Chicago Transit Authority	0.939	0.527	0.480	0.740	0.322
	San Francisco Bay Area Rapid Transit District	0.679	0.771	0.321	0.864	0.505
	Los Angeles County Metropolitan Transportation Authority	0.830	0.769	0.611	0.713	0.160
Light Rail Systems	Tri-County Metropolitan Transportation District of Oregon	0.869	0.350	0.713	0.392	0.060
	Central Puget Sound Regional Transit Authority	0.514	0.867	0.495	0.697	0.200
	Massachusetts Bay Transportation Authority	0.667	0.587	0.702	0.519	0.112
	Niagara Frontier Transportation Authority	0.360	0.692	0.513	0.690	0.064
	Port Authority of Allegheny County	0.385	0.761	0.432	0.490	0.036
	Maryland Transit Administration	0.226	0.727	0.753	0.266	0.048
	Charlotte Area Transit System	0.563	0.637	0.578	0.421	0.117
	The Greater Cleveland Regional Transit Authority	0.702	0.494	0.550	0.562	0.036
	Metro Transit	0.829	0.503	0.507	0.440	0.140
	Metropolitan Transit Authority of Harris County, Texas	0.288	0.527	0.617	0.212	0.035
	Dallas Area Rapid Transit	0.637	0.460	0.493	0.434	0.114
	Bi-State Development Agency	0.349	1.000	0.635	0.299	0.052

	Utah Transit Authority	0.349	0.602	0.552	0.279	0.020
	Denver Regional Transportation District	0.366	0.435	0.687	0.176	0.043
	Santa Clara Valley Transportation Authority	0.550	0.673	0.531	0.326	0.065
	San Francisco Municipal Railway	0.452	0.503	0.627	0.248	0.050
	Sacramento Regional Transit District	0.413	0.628	0.638	0.255	0.005
	San Diego Metropolitan Transit System	0.375	0.505	0.490	0.251	0.032
	Los Angeles County Metropolitan Transportation Authority	0.219	0.483	0.483	0.220	0.039
	Valley Metro Rail, Inc.	0.352	0.464	0.490	0.284	0.017

Table 6-65 Social Rescaling Calculations

	Operator Name	Affordability	Average Journey Length	System Accessibility	User Accessibility
Heavy Rail Systems	Massachusetts Bay Transportation Authority	0.691	0.572	1.000	0.188
	MTA New York City Transit	0.252	0.177	0.204	1.000
	Port Authority Trans-Hudson Corporation	0.758	0.470	0.003	1.000
	Staten Island Rapid Transit Operating Authority	0.537	0.372	0.022	1.000
	Southeastern Pennsylvania Transportation Authority	1.000	0.856	0.827	1.000
	Washington Metropolitan Area Transit Authority	0.836	0.317	0.004	1.000
	Maryland Transit Administration	0.646	0.463	0.069	1.000
	Metropolitan Atlanta Rapid Transit Authority	0.992	1.000	0.001	1.000
	Miami-Dade Transit	0.540	0.316	0.061	1.000
	The Greater Cleveland Regional Transit Authority	0.712	0.359	0.018	1.000
	Chicago Transit Authority	0.516	0.370	0.403	0.629
	San Francisco Bay Area Rapid Transit District	0.488	0.400	0.090	1.000
	Los Angeles County Metropolitan Transportation Authority	0.694	0.514	0.235	0.400

	Operator Name	Affordability	Average Journey Length	System Accessibility	User Accessibility
Light Rail Systems	Tri-County Metropolitan Transportation District of Oregon	0.664	0.315	0.009	1.000
	Central Puget Sound Regional Transit Authority	0.668	0.656	0.017	0.925
	Massachusetts Bay Transportation Authority	0.632	0.533	0.070	1.000
	Niagara Frontier Transportation Authority	0.692	0.960	0.006	0.486
	Port Authority of Allegheny County	0.539	0.537	0.029	0.538
	Maryland Transit Administration	0.712	0.869	0.085	1.000
	Charlotte Area Transit System	0.585	0.423	0.040	0.979
	The Greater Cleveland Regional Transit Authority	0.650	0.430	0.006	1.000
	Metro Transit	0.518	0.263	0.020	1.000
	Metropolitan Transit Authority of Harris County, Texas	0.861	0.444	0.031	1.000
	Dallas Area Rapid Transit	0.571	0.328	0.035	1.000
	Bi-State Development Agency	0.776	0.531	0.010	1.000
	Utah Transit Authority	0.552	0.432	0.013	1.000
	Denver Regional Transportation District	0.696	0.323	0.005	1.000
	Santa Clara Valley Transportation Authority	0.498	0.308	0.006	1.000
	San Francisco Municipal Railway	0.767	0.337	0.010	1.000
	Sacramento Regional Transit District	0.795	0.386	0.076	0.217
	San Diego Metropolitan Transit System	0.472	0.322	0.006	0.722
	Los Angeles County Metropolitan Transportation Authority	0.490	0.474	0.006	1.000
	Valley Metro Rail, Inc.	0.472	0.387	0.003	0.265

Table 6-66 System Effectiveness Rescaling Calculations

	Operator Name	pkm/theoretical pkm	Annual trips/capita
Heavy Rail Systems	Massachusetts Bay Transportation Authority	0.515	1.000
	MTA New York City Transit	0.452	0.112
	Port Authority Trans-Hudson Corporation	1.000	0.014
	Staten Island Rapid Transit Operating Authority	0.355	0.038
	Southeastern Pennsylvania Transportation Authority	0.347	0.206
	Washington Metropolitan Area Transit Authority	0.700	0.013
	Maryland Transit Administration	0.475	0.090
	Metropolitan Atlanta Rapid Transit Authority	0.360	0.017
	Miami-Dade Transit	0.231	0.043
	The Greater Cleveland Regional Transit Authority	0.328	0.012
	Chicago Transit Authority	0.658	0.085
	San Francisco Bay Area Rapid Transit District	0.397	0.245
	Los Angeles County Metropolitan Transportation Authority	0.634	0.062
Light Rail Systems	Tri-County Metropolitan Transportation District of Oregon	0.438	0.014
	Central Puget Sound Regional Transit Authority	0.262	0.116
	Massachusetts Bay Transportation Authority	0.438	0.051
	Niagara Frontier Transportation Authority	0.409	0.054
	Port Authority of Allegheny County	0.581	0.032
	Maryland Transit Administration	0.368	0.080
	Charlotte Area Transit System	0.257	0.037
	The Greater Cleveland Regional Transit Authority	0.369	0.015
	Metro Transit	0.392	0.026
	Metropolitan Transit Authority of Harris County, Texas	0.320	0.021
	Dallas Area Rapid Transit	0.277	0.034

	Bi-State Development Agency	0.232	0.022
	Utah Transit Authority	0.258	0.015
	Denver Regional Transportation District	0.382	0.014
	Santa Clara Valley Transportation Authority	0.292	0.012
	San Francisco Municipal Railway	0.288	0.013
	Sacramento Regional Transit District	0.306	0.054
	San Diego Metropolitan Transit System	0.540	0.007
	Los Angeles County Metropolitan Transportation Authority	0.294	0.013
	Valley Metro Rail, Inc.	0.437	0.004

With all values re-scaled, categorical indices can now be calculated based on the weighting assumptions stated earlier in this chapter. The category values are shown in Table 6-67.

Table 6-67 Category Indices for Method 3

	Operator Name	EI	EcI	SI	SeI
Heavy Rail Systems	Massachusetts Bay Transportation Authority	0.577	0.860	0.613	0.758
	MTA New York City Transit	0.722	0.639	0.408	0.282
	Port Authority Trans-Hudson Corporation	0.392	0.592	0.558	0.507
	Staten Island Rapid Transit Operating Authority	0.710	0.583	0.483	0.197
	Southeastern Pennsylvania Transportation Authority	0.357	0.383	0.921	0.277
	Washington Metropolitan Area Transit Authority	0.508	0.468	0.539	0.357
	Maryland Transit Administration	0.553	0.489	0.545	0.283
	Metropolitan Atlanta Rapid Transit Authority	0.304	0.598	0.748	0.188
	Miami-Dade Transit	0.833	0.340	0.479	0.137
	The Greater Cleveland Regional Transit Authority	0.417	0.620	0.522	0.170
	Chicago Transit Authority	0.274	0.602	0.480	0.371
	San Francisco Bay Area Rapid Transit District	0.228	0.628	0.494	0.321
	Los Angeles County Metropolitan Transportation Authority	0.228	0.617	0.461	0.348
Light Rail Systems	Tri-County Metropolitan Transportation District of Oregon	0.367	0.477	0.497	0.226
	Central Puget Sound Regional Transit Authority	0.214	0.555	0.567	0.189
	Massachusetts Bay Transportation Authority	0.198	0.517	0.559	0.244
	Niagara Frontier Transportation Authority	0.261	0.464	0.536	0.232
	Port Authority of Allegheny County	0.354	0.421	0.411	0.307
	Maryland Transit Administration	0.179	0.404	0.666	0.224
	Charlotte Area Transit System	0.345	0.463	0.507	0.147
	The Greater Cleveland Regional Transit Authority	0.249	0.469	0.522	0.192
	Metro Transit	0.284	0.484	0.450	0.209
	Metropolitan Transit Authority of Harris County, Texas	0.327	0.336	0.584	0.171
	Dallas Area Rapid Transit	0.233	0.428	0.484	0.156
	Bi-State Development Agency	0.098	0.467	0.579	0.127
	Utah Transit Authority	0.218	0.360	0.499	0.136
	Denver Regional Transportation District	0.155	0.341	0.506	0.198
	Santa Clara Valley Transportation Authority	0.153	0.429	0.453	0.152
	San Francisco Municipal Railway	0.128	0.376	0.528	0.150
	Sacramento Regional Transit District	0.204	0.388	0.368	0.180
	San Diego Metropolitan Transit System	0.074	0.331	0.380	0.273
	Los Angeles County Metropolitan Transportation Authority	0.088	0.289	0.493	0.154
	Valley Metro Rail, Inc.	0.090	0.322	0.282	0.221

Using default weighting values, CSI values have been calculated from the category index values.

Table 6-68 CSI Values for Method 3

	Operator Name	CSI
Heavy Rail Systems	MTA New York City Transit	0.702
	Los Angeles County Metropolitan Transportation Authority	0.513
	Chicago Transit Authority	0.512
	San Francisco Municipal Railway	0.493
	Los Angeles County Metropolitan Transportation Authority	0.484
	Tri-County Metropolitan Transportation District of Oregon	0.468
	Metropolitan Transit Authority of Harris County, Texas	0.467
	San Diego Metropolitan Transit System	0.460
	Southeastern Pennsylvania Transportation Authority	0.448
	Metropolitan Atlanta Rapid Transit Authority	0.432
	Massachusetts Bay Transportation Authority	0.432
	Washington Metropolitan Area Transit Authority	0.418
	Port Authority Trans-Hudson Corporation	0.413
Light Rail Systems	Utah Transit Authority	0.392
	Valley Metro Rail, Inc.	0.381
	Massachusetts Bay Transportation Authority	0.379
	San Francisco Bay Area Rapid Transit District	0.373
	Metro Transit	0.373
	Sacramento Regional Transit District	0.368
	Bi-State Development Agency	0.366
	Niagara Frontier Transportation Authority	0.358
	Central Puget Sound Regional Transit Authority	0.357
	Santa Clara Valley Transportation Authority	0.354
	Denver Regional Transportation District	0.325
	Charlotte Area Transit System	0.318
	Miami-Dade Transit	0.303
	Staten Island Rapid Transit Operating Authority	0.300
	Dallas Area Rapid Transit	0.297
	Maryland Transit Administration	0.296
	Maryland Transit Administration	0.285
	Port Authority of Allegheny County	0.265
	The Greater Cleveland Regional Transit Authority	0.256
	The Greater Cleveland Regional Transit Authority	0.229

6.7 CSI Results Analysis

This section provides commentary on the results of the category and composite sustainability index analysis. The quartile performance break down used in the factor analysis is reused here to offer up further commentary on overall performance of the systems based on the default weightings. This default weighting is considered the base case scenario. Under this scenario it is assumed all factors have identical value and all categories are valued equally. Systems are also sorted into performance categories based on their ranking under each index to add a secondary analysis to go along with the CSI measure. Section 6.8 outlines sensitivity testing based on changes to weightings of the index level scores to explore how rankings and CSI values change with different categorical indices.

6.7.1 Method 1: z-score

Referring to the category indices for both system sets it is important to observe that aside from MTA New York city, no system achieves a high degree of performance in all 4 categories in either system set. This reflects the notion that developing a system that is optimized for all elements of sustainability mobility is a complex process with many competing factors and trade-offs. Some systems are able to achieve performance spikes in individual categories, such as San Francisco Bay Area Rapid Transit District's high score of 0.907 in the EI category or San Francisco Municipal Railway 's score of 1.607 under SI. These systems however do not achieve high performance in the other three factors. Other systems can be characterized as balanced performance, with above average performance in 3 out of 4 factors, such as Chicago Transit Authority that achieves high or highest performance in indices. Systems are sorted into the following performance categories:

- **Specialized Performance:** Highest/high performance under 1-2 indices, the remaining are low or poorest.
- **Balanced Performance (high):** High or highest performance in ¾ indices
- **Balanced Performance (medium):** 3-4 indices above poor performance. 1 index above low performance
- **Low Performance:** low or poorest performance across all indices

- **Superior Performance:** Highest performance across all 4 factors

To aid in sorting and analysis performance tables for each system by each index are listed below in Table 6-69, Table 6-70, Table 6-71, and Table 6-72. These tables also include the numbers of each system in each performance tier – for example, there are 5 LR and 3 HR systems under the highest performance tear in the environmental index (EI).

Table 6-69 EI Ranking For Method 1

Rank	Operator Name	Mode	EI	Performance
1	San Francisco Bay Area Rapid Transit District	HR	0.907	Highest
2	MTA New York City Transit	HR	0.902	LR
3	San Diego Metropolitan Transit System	LR	0.900	5
4	Central Puget Sound Regional Transit Authority	LR	0.891	HR
5	Tri-County Metropolitan Transportation District of Oregon	LR	0.815	3
6	Los Angeles County Metropolitan Transportation Authority	LR	0.726	
7	Metropolitan Atlanta Rapid Transit Authority	HR	0.663	
8	Valley Metro Rail, Inc.	LR	0.638	
9	Port Authority Trans-Hudson Corporation	HR	0.618	High
10	Los Angeles County Metropolitan Transportation Authority	HR	0.546	LR
11	San Francisco Municipal Railway	LR	0.468	6
12	Metropolitan Transit Authority of Harris County, Texas	LR	0.461	HR
13	Sacramento Regional Transit District	LR	0.438	3
14	Santa Clara Valley Transportation Authority	LR	0.388	
15	Chicago Transit Authority	HR	0.356	
16	Massachusetts Bay Transportation Authority	LR	0.345	
17	Bi-State Development Agency	LR	0.289	
18	Metro Transit	LR	0.205	Low
19	Massachusetts Bay Transportation Authority	HR	0.127	LR
20	Southeastern Pennsylvania Transportation Authority	HR	0.126	5
21	Denver Regional Transportation District	LR	0.119	HR
22	Staten Island Rapid Transit Operating Authority	HR	0.104	4
23	Charlotte Area Transit System	LR	0.096	
24	Niagara Frontier Transportation Authority	LR	-0.067	
25	Washington Metropolitan Area Transit Authority	HR	-0.112	
26	Utah Transit Authority	LR	-0.197	
27	Miami-Dade Transit	HR	-0.374	Poorest
28	Dallas Area Rapid Transit	LR	-0.377	LR
29	Maryland Transit Administration	LR	-0.979	4
30	Maryland Transit Administration	HR	-1.686	HR
31	Port Authority of Allegheny County	LR	-1.966	3
32	The Greater Cleveland Regional Transit Authority	LR	-2.223	
33	The Greater Cleveland Regional Transit Authority	HR	-2.999	

Table 6-70 EcI Ranking For Method 1

Rank	Operator Name	Mode	EcI	Performance
1	MTA New York City Transit	HR	1.773	Highest
2	Washington Metropolitan Area Transit Authority	HR	0.721	LR
3	Southeastern Pennsylvania Transportation Authority	HR	0.680	1
4	Metropolitan Atlanta Rapid Transit Authority	HR	0.605	HR
5	Massachusetts Bay Transportation Authority	HR	0.528	7
6	Los Angeles County Metropolitan Transportation Authority	HR	0.510	
7	Metropolitan Transit Authority of Harris County, Texas	LR	0.505	
8	Chicago Transit Authority	HR	0.492	
9	San Diego Metropolitan Transit System	LR	0.340	High
10	Utah Transit Authority	LR	0.265	LR
11	Sacramento Regional Transit District	LR	0.114	8
12	Tri-County Metropolitan Transportation District of Oregon	LR	0.107	HR
13	Massachusetts Bay Transportation Authority	LR	0.098	1
14	Maryland Transit Administration	HR	0.036	
15	Bi-State Development Agency	LR	0.006	
16	Metro Transit	LR	-0.011	
17	Los Angeles County Metropolitan Transportation Authority	LR	-0.022	
18	Miami-Dade Transit	HR	-0.028	Low
19	San Francisco Bay Area Rapid Transit District	HR	-0.031	LR
20	Port Authority Trans-Hudson Corporation	HR	-0.099	5
21	Denver Regional Transportation District	LR	-0.203	HR
22	Staten Island Rapid Transit Operating Authority	HR	-0.242	4
23	Maryland Transit Administration	LR	-0.357	
24	Valley Metro Rail, Inc.	LR	-0.373	
25	Charlotte Area Transit System	LR	-0.393	
26	Niagara Frontier Transportation Authority	LR	-0.430	
27	San Francisco Municipal Railway	LR	-0.462	Poorest
28	The Greater Cleveland Regional Transit Authority	HR	-0.573	LR
29	Central Puget Sound Regional Transit Authority	LR	-0.582	6
30	Santa Clara Valley Transportation Authority	LR	-0.621	HR
31	Dallas Area Rapid Transit	LR	-0.646	1
32	The Greater Cleveland Regional Transit Authority	LR	-0.679	
33	Port Authority of Allegheny County	LR	-1.030	

Table 6-71 SI Ranking for Method 1

Rank	Operator Name	Mode	SI	Performance
1	San Francisco Municipal Railway	LR	1.607	Highest
2	Metropolitan Transit Authority of Harris County, Texas	LR	0.734	LR
3	MTA New York City Transit	HR	0.652	5
4	Niagara Frontier Transportation Authority	LR	0.596	HR
5	Maryland Transit Administration	HR	0.367	3
6	Santa Clara Valley Transportation Authority	LR	0.349	
7	Massachusetts Bay Transportation Authority	HR	0.302	
8	Utah Transit Authority	LR	0.294	
9	Los Angeles County Metropolitan Transportation Authority	HR	0.277	High
10	Tri-County Metropolitan Transportation District of Oregon	LR	0.232	LR
11	Metro Transit	LR	0.121	7
12	Metropolitan Atlanta Rapid Transit Authority	HR	0.071	HR
13	Maryland Transit Administration	LR	0.060	2
14	Los Angeles County Metropolitan Transportation Authority	LR	0.054	
15	Sacramento Regional Transit District	LR	0.046	
16	Massachusetts Bay Transportation Authority	LR	0.031	
17	Charlotte Area Transit System	LR	0.000	
18	Dallas Area Rapid Transit	LR	-0.044	Low
19	Southeastern Pennsylvania Transportation Authority	HR	-0.045	LR
20	Port Authority of Allegheny County	LR	-0.060	6
21	Washington Metropolitan Area Transit Authority	HR	-0.079	HR
22	Chicago Transit Authority	HR	-0.087	3
23	Valley Metro Rail, Inc.	LR	-0.095	
24	San Diego Metropolitan Transit System	LR	-0.116	
25	Denver Regional Transportation District	LR	-0.148	
26	Central Puget Sound Regional Transit Authority	LR	-0.198	
27	Port Authority Trans-Hudson Corporation	HR	-0.316	Poorest
28	Miami-Dade Transit	HR	-0.358	LR
29	Bi-State Development Agency	LR	-0.457	2
30	Staten Island Rapid Transit Operating Authority	HR	-0.485	HR
31	The Greater Cleveland Regional Transit Authority	HR	-0.637	5
32	The Greater Cleveland Regional Transit Authority	LR	-0.929	
33	San Francisco Bay Area Rapid Transit District	HR	-1.737	

Table 6-72 SeI Ranking for Method 1

Rank	Operator Name	Mode	SeI	Performance
1	MTA New York City Transit	HR	2.96	Highest
2	Los Angeles County Metropolitan Transportation Authority	HR	1.63	LR
3	Chicago Transit Authority	HR	0.78	2
4	Los Angeles County Metropolitan Transportation Authority	LR	0.70	HR
5	Southeastern Pennsylvania Transportation Authority	HR	0.64	6
6	Washington Metropolitan Area Transit Authority	HR	0.43	
7	Port Authority Trans-Hudson Corporation	HR	0.39	
8	Tri-County Metropolitan Transportation District of Oregon	LR	0.23	
9	San Francisco Bay Area Rapid Transit District	HR	0.22	High
10	The Greater Cleveland Regional Transit Authority	HR	0.19	LR
11	San Francisco Municipal Railway	LR	0.17	7
12	Utah Transit Authority	LR	0.00	HR
13	Massachusetts Bay Transportation Authority	LR	-0.08	2
14	Valley Metro Rail, Inc.	LR	-0.10	
15	Niagara Frontier Transportation Authority	LR	-0.13	
16	The Greater Cleveland Regional Transit Authority	LR	-0.13	
17	Bi-State Development Agency	LR	-0.21	
18	Dallas Area Rapid Transit	LR	-0.27	Low
19	San Diego Metropolitan Transit System	LR	-0.29	LR
20	Metro Transit	LR	-0.31	6
21	Metropolitan Transit Authority of Harris County, Texas	LR	-0.34	HR
22	Massachusetts Bay Transportation Authority	HR	-0.35	3
23	Staten Island Rapid Transit Operating Authority	HR	-0.40	
24	Santa Clara Valley Transportation Authority	LR	-0.44	
25	Metropolitan Atlanta Rapid Transit Authority	HR	-0.45	
26	Denver Regional Transportation District	LR	-0.54	
27	Port Authority of Allegheny County	LR	-0.55	Poorest
28	Miami-Dade Transit	HR	-0.56	LR
29	Maryland Transit Administration	LR	-0.57	5
30	Sacramento Regional Transit District	LR	-0.60	HR
31	Charlotte Area Transit System	LR	-0.66	2
32	Central Puget Sound Regional Transit Authority	LR	-0.66	
33	Maryland Transit Administration	HR	-0.72	

From these tables, it can be observed that with base weightings and the factors selected for this study that in the NTD data set:

- For the environmental factors, LR systems achieve the highest performance in general
- For economic factors, HR systems achieve the highest performance in general
- For social factors, LR systems achieve the highest performance in general
- For system effectiveness factors, HR systems achieve the highest performance factors in general

These observations are in line with the factor analysis conducted in 6.5 that found general LR performance to be superior in the environmental and social factors, and HR performance to be superior in the economic and system effectiveness categories. However, it is important to note that these general findings do not indicate that high performing HR systems do not achieve similar levels of performance to LR systems under the environmental and social categories. Rather they indicate relative populations in the ranking table and are intended to be useful conclusions when considering relative performance. The same can be said about the high performing LR systems that achieve comparable performance to HR systems under the economic and system effectiveness factors. Similar to past conclusions, while there are general performance classes that emerge, it can also be observed that regardless of modal technology, high performance can be achieved under all sustainability criteria.

Each system has been assigned a performance designation based on their categorical indices. Systems and their designations are listed in Table 6-73. These classifications are used to interpret the systems in addition to the CSI results.

Table 6-73 System Designations for Method 1

Operator Name	Mode	Classification
Massachusetts Bay Transportation Authority	HR	Balanced Performance (High)
Metropolitan Atlanta Rapid Transit Authority	HR	Balanced Performance (High)
Chicago Transit Authority	HR	Balanced Performance (High)
Los Angeles County Metropolitan Transportation Authority	HR	Balanced Performance (High)
Tri-County Metropolitan Transportation District of Oregon	LR	Balanced Performance (High)
Massachusetts Bay Transportation Authority	LR	Balanced Performance (High)
Metropolitan Transit Authority of Harris County, Texas	LR	Balanced Performance (High)
Utah Transit Authority	LR	Balanced Performance (High)
San Francisco Municipal Railway	LR	Balanced Performance (High)
Sacramento Regional Transit District	LR	Balanced Performance (High)
Los Angeles County Metropolitan Transportation Authority	LR	Balanced Performance (High)
Maryland Transit Administration	HR	Balanced Performance (Medium)
Metro Transit	LR	Balanced Performance (Medium)
Bi-State Development Agency	LR	Balanced Performance (Medium)
Staten Island Rapid Transit Operating Authority	HR	Low Performance
Miami-Dade Transit	HR	Low Performance
The Greater Cleveland Regional Transit Authority	HR	Low Performance
Port Authority of Allegheny County	LR	Low Performance
Maryland Transit Administration	LR	Low Performance
Charlotte Area Transit System	LR	Low Performance
The Greater Cleveland Regional Transit Authority	LR	Low Performance
Dallas Area Rapid Transit	LR	Low Performance
Denver Regional Transportation District	LR	Low Performance
Port Authority Trans-Hudson Corporation	HR	Specialized Performance
Southeastern Pennsylvania Transportation Authority	HR	Specialized Performance
Washington Metropolitan Area Transit Authority	HR	Specialized Performance
San Francisco Bay Area Rapid Transit District	HR	Specialized Performance
Central Puget Sound Regional Transit Authority	LR	Specialized Performance
Niagara Frontier Transportation Authority	LR	Specialized Performance
Santa Clara Valley Transportation Authority	LR	Specialized Performance
San Diego Metropolitan Transit System	LR	Specialized Performance
Valley Metro Rail, Inc.	LR	Specialized Performance
MTA New York City Transit	HR	Superior Performance

The results of the CSI calculation have been sorted by rank and then segmented into performance quartiles. These results are shown in table 6-74.

Table 6-74 CSI Method 1 Ranking

Rank	Operator Name	Mode	CSI	Performance
1	MTA New York City Transit	HR	1.573	Highest
2	Los Angeles County Metropolitan Transportation Authority	HR	0.741	LR
3	San Francisco Municipal Railway	LR	0.445	4
4	Chicago Transit Authority	HR	0.385	HR
5	Los Angeles County Metropolitan Transportation Authority	LR	0.365	4
6	Tri-County Metropolitan Transportation District of Oregon	LR	0.346	
7	Metropolitan Transit Authority of Harris County, Texas	LR	0.341	
8	Southeastern Pennsylvania Transportation Authority	HR	0.335	
9	Metropolitan Atlanta Rapid Transit Authority	HR	0.223	High
10	Washington Metropolitan Area Transit Authority	HR	0.219	LR
11	San Diego Metropolitan Transit System	LR	0.209	5
12	Massachusetts Bay Transportation Authority	HR	0.151	HR
13	Port Authority Trans-Hudson Corporation	HR	0.148	4
14	Massachusetts Bay Transportation Authority	LR	0.099	
15	Utah Transit Authority	LR	0.091	
16	Valley Metro Rail, Inc.	LR	0.017	
17	Sacramento Regional Transit District	LR	0.0004	
18	Metro Transit	LR	0.00001	Low
19	Niagara Frontier Transportation Authority	LR	-0.008	LR
20	Santa Clara Valley Transportation Authority	LR	-0.082	7
21	Bi-State Development Agency	LR	-0.093	HR
22	Central Puget Sound Regional Transit Authority	LR	-0.136	2
23	San Francisco Bay Area Rapid Transit District	HR	-0.159	
24	Denver Regional Transportation District	LR	-0.193	
25	Charlotte Area Transit System	LR	-0.238	
26	Staten Island Rapid Transit Operating Authority	HR	-0.255	
27	Miami-Dade Transit	HR	-0.330	Poorest
28	Dallas Area Rapid Transit	LR	-0.335	LR
29	Maryland Transit Administration	LR	-0.461	4
30	Maryland Transit Administration	HR	-0.500	HR
31	Port Authority of Allegheny County	LR	-0.901	3
32	The Greater Cleveland Regional Transit Authority	LR	-0.991	
33	The Greater Cleveland Regional Transit Authority	HR	-1.005	

As observed in the table, the highest performing systems are Heavy Rail systems; however the population in the highest performance categories is balanced between Heavy and Light Rail indicating that both systems can achieve comparable sustainability performance based on the weighing and criteria used in this study.

However, the majority of HR systems (8/13) are ranked in the highest performance categories, compared to less than half of the LR systems (9/20). In general, the highest performing HR systems outperform the highest performing LR systems and the high performance HR systems outperform the high performance LR systems. However, with the exception of MTA New York and Los Angeles County Metropolitan Transit Authority, the two top HR systems, the differences between the closely ranked HR and LR systems are small, indicating comparable performance is possible between the modes.

6.7.2 Method 2: Utility

A similar approach is utilized to classify and analyze results for method 2 as for method one. As additional technique to interpret results is employed for the utility method based on Jeon (2007). Jeon 2007 was the source of the utility formula and also utilized radar graphs to display results. This technique will also be used to demonstrate differences under each sustainability category for the top 5 systems for the method 2 CSI results.

First, the performance under each category based on quartiles is shown in Table 6-75, Table 6-76, Table 6-77, and Table 6-78.

Table 6-75 EI Ranking for Method 2

Rank	Operator Name	Mode	EI	Performance
1	Central Puget Sound Regional Transit Authority	LR	0.833	Highest
2	San Francisco Bay Area Rapid Transit District	HR	0.722	LR
3	San Diego Metropolitan Transit System	LR	0.710	4
4	MTA New York City Transit	HR	0.577	HR
5	Tri-County Metropolitan Transportation District of Oregon	LR	0.553	4
6	Los Angeles County Metropolitan Transportation Authority	LR	0.508	
7	Metropolitan Atlanta Rapid Transit Authority	HR	0.417	
8	Los Angeles County Metropolitan Transportation Authority	HR	0.392	
9	Valley Metro Rail, Inc.	LR	0.367	High
10	San Francisco Municipal Railway	LR	0.357	LR
11	Port Authority Trans-Hudson Corporation	HR	0.354	7
12	Sacramento Regional Transit District	LR	0.345	HR
13	Santa Clara Valley Transportation Authority	LR	0.327	2
14	Metropolitan Transit Authority of Harris County, Texas	LR	0.304	
15	Bi-State Development Agency	LR	0.284	
16	Chicago Transit Authority	HR	0.274	
17	Massachusetts Bay Transportation Authority	LR	0.261	
18	Metro Transit	LR	0.249	Low
19	Denver Regional Transportation District	LR	0.233	LR
20	Southeastern Pennsylvania Transportation Authority	HR	0.228	5
21	Washington Metropolitan Area Transit Authority	HR	0.228	HR
22	Charlotte Area Transit System	LR	0.218	4
23	Massachusetts Bay Transportation Authority	HR	0.214	
24	Staten Island Rapid Transit Operating Authority	HR	0.204	
25	Utah Transit Authority	LR	0.198	
26	Niagara Frontier Transportation Authority	LR	0.179	
27	Dallas Area Rapid Transit	LR	0.155	Poorest
28	Miami-Dade Transit	HR	0.153	LR
29	Maryland Transit Administration	LR	0.128	4
30	Maryland Transit Administration	HR	0.098	HR
31	The Greater Cleveland Regional Transit Authority	LR	0.090	3
32	Port Authority of Allegheny County	LR	0.088	
33	The Greater Cleveland Regional Transit Authority	HR	0.074	

Table 6-76 EcI Ranking for Method 2

Rank	Operator Name	Mode	EcI	Performance
1	MTA New York City Transit	HR	0.860	Highest
2	San Francisco Bay Area Rapid Transit District	HR	0.639	LR
3	Washington Metropolitan Area Transit Authority	HR	0.628	1
4	Metropolitan Atlanta Rapid Transit Authority	HR	0.620	HR
5	Southeastern Pennsylvania Transportation Authority	HR	0.617	7
6	Chicago Transit Authority	HR	0.602	
7	Metropolitan Transit Authority of Harris County, Texas	LR	0.598	
8	Los Angeles County Metropolitan Transportation Authority	HR	0.592	
9	San Diego Metropolitan Transit System	LR	0.583	High
10	Massachusetts Bay Transportation Authority	HR	0.555	LR
11	Utah Transit Authority	LR	0.517	7
12	Tri-County Metropolitan Transportation District of Oregon	LR	0.489	HR
13	Bi-State Development Agency	LR	0.484	2
14	Valley Metro Rail, Inc.	LR	0.477	
15	Metro Transit	LR	0.469	
16	Los Angeles County Metropolitan Transportation Authority	LR	0.468	
17	Maryland Transit Administration	HR	0.467	
18	Massachusetts Bay Transportation Authority	LR	0.464	Low
19	Sacramento Regional Transit District	LR	0.463	LR
20	Miami-Dade Transit	HR	0.429	6
21	Denver Regional Transportation District	LR	0.428	HR
22	Port Authority Trans-Hudson Corporation	HR	0.421	3
23	Niagara Frontier Transportation Authority	LR	0.404	
24	Staten Island Rapid Transit Operating Authority	HR	0.388	
25	San Francisco Municipal Railway	LR	0.383	
26	Maryland Transit Administration	LR	0.376	
27	Charlotte Area Transit System	LR	0.360	Poorest
28	Dallas Area Rapid Transit	LR	0.341	LR
29	Central Puget Sound Regional Transit Authority	LR	0.340	6
30	Santa Clara Valley Transportation Authority	LR	0.336	HR
31	The Greater Cleveland Regional Transit Authority	HR	0.331	1
32	The Greater Cleveland Regional Transit Authority	LR	0.322	
33	Port Authority of Allegheny County	LR	0.289	

Table 6-77 SI Ranking for Method 2

Rank	Operator Name	Mode	SI	Performance
1	San Francisco Municipal Railway	LR	0.921	Highest
2	Metropolitan Transit Authority of Harris County, Texas	LR	0.748	LR
3	Niagara Frontier Transportation Authority	LR	0.666	5
4	MTA New York City Transit	HR	0.613	HR
5	Santa Clara Valley Transportation Authority	LR	0.584	3
6	Maryland Transit Administration	HR	0.579	
7	Massachusetts Bay Transportation Authority	HR	0.567	
8	Utah Transit Authority	LR	0.559	
9	Los Angeles County Metropolitan Transportation Authority	HR	0.558	High
10	Tri-County Metropolitan Transportation District of Oregon	LR	0.545	LR
11	Los Angeles County Metropolitan Transportation Authority	LR	0.539	7
12	Massachusetts Bay Transportation Authority	LR	0.536	HR
13	Maryland Transit Administration	LR	0.528	2
14	Metropolitan Atlanta Rapid Transit Authority	HR	0.522	
15	Metro Transit	LR	0.522	
16	Sacramento Regional Transit District	LR	0.507	
17	Dallas Area Rapid Transit	LR	0.506	
18	Charlotte Area Transit System	LR	0.499	Low
19	Valley Metro Rail, Inc.	LR	0.497	LR
20	Washington Metropolitan Area Transit Authority	HR	0.494	6
21	Port Authority of Allegheny County	LR	0.493	HR
22	Denver Regional Transportation District	LR	0.484	3
23	San Diego Metropolitan Transit System	LR	0.483	
24	Chicago Transit Authority	HR	0.480	
25	Central Puget Sound Regional Transit Authority	LR	0.479	
26	Southeastern Pennsylvania Transportation Authority	HR	0.461	
27	Miami-Dade Transit	HR	0.453	Poorest
28	Bi-State Development Agency	LR	0.450	LR
29	Port Authority Trans-Hudson Corporation	HR	0.411	2
30	San Francisco Bay Area Rapid Transit District	HR	0.408	HR
31	The Greater Cleveland Regional Transit Authority	HR	0.380	5
32	Staten Island Rapid Transit Operating Authority	HR	0.368	
33	The Greater Cleveland Regional Transit Authority	LR	0.282	

Table 6-78 SeI Ranking for Method 2

Rank	Operator Name	Mode	SeI	Performance
1	MTA New York City Transit	HR	0.758	Highest
2	Los Angeles County Metropolitan Transportation Authority	HR	0.507	LR
3	Chicago Transit Authority	HR	0.371	2
4	Los Angeles County Metropolitan Transportation Authority	LR	0.357	HR
5	Southeastern Pennsylvania Transportation Authority	HR	0.348	6
6	Washington Metropolitan Area Transit Authority	HR	0.321	
7	Port Authority Trans-Hudson Corporation	HR	0.307	
8	Tri-County Metropolitan Transportation District of Oregon	LR	0.283	
9	San Francisco Bay Area Rapid Transit District	HR	0.282	High
10	San Francisco Municipal Railway	LR	0.277	LR
11	The Greater Cleveland Regional Transit Authority	HR	0.273	7
12	Utah Transit Authority	LR	0.244	HR
13	Massachusetts Bay Transportation Authority	LR	0.232	2
14	Valley Metro Rail, Inc.	LR	0.226	
15	Niagara Frontier Transportation Authority	LR	0.224	
16	The Greater Cleveland Regional Transit Authority	LR	0.221	
17	Bi-State Development Agency	LR	0.209	
18	Dallas Area Rapid Transit	LR	0.198	Low
19	San Diego Metropolitan Transit System	LR	0.197	LR
20	Metro Transit	LR	0.192	6
21	Massachusetts Bay Transportation Authority	HR	0.189	HR
22	Metropolitan Transit Authority of Harris County, Texas	LR	0.188	3
23	Staten Island Rapid Transit Operating Authority	HR	0.180	
24	Santa Clara Valley Transportation Authority	LR	0.171	
25	Metropolitan Atlanta Rapid Transit Authority	HR	0.170	
26	Denver Regional Transportation District	LR	0.156	
27	Port Authority of Allegheny County	LR	0.154	Poorest
28	Miami-Dade Transit	HR	0.152	LR
29	Maryland Transit Administration	LR	0.150	5
30	Sacramento Regional Transit District	LR	0.147	HR
31	Central Puget Sound Regional Transit Authority	LR	0.137	2
32	Charlotte Area Transit System	LR	0.136	
33	Maryland Transit Administration	HR	0.127	

As this method compares each system to the highest performer, rather than the average, in order to calculate the indices, there are some differences compared to method 1. The overall trends observed in this data set are:

- In the environmental category, the general trend is for LR systems to achieve greater performance based on a criterion analyzing the highest and high performance categories. While there were 4 systems of each set in the highest category, the high category contains 7 LR, compared to 2 HR. However, it can be observed in this method, that for the highest systems relatively similar levels of performance can be achieved.
- In the economic category, the highest category is populated with 7 HR systems and 1 LR system, indicating overall superior performance by HR for this category. Similar to the last indicator, the high category has more LR than HR systems (7 to 2); however the performance levels are quite similar between all systems. This indicates that high level LR systems perform at a similar level to middle level HR systems.
- In the social category, there are 5 LR and 3 HR in the highest performance category and a similar 7 to 2 split as seen in the environmental and economic categories. This indicates a performance advantage by the LR systems, with High level HR systems competing with mid-level LR systems.
- In the system effectiveness category, 6 HR systems populate the highest category, compared to 2 LR, while the same 7 to 2 split occurs in the high category. Again, this indicated that the best performing LR out perform with the second tier of HR systems.

The overall results do not differ greatly from methodology 1 – populations may shift by 1 between methodologies. However, there is a difference between the rankings that each system receives. Again, as this method is based on the highest performer, rather than the mean, the values a system receives in the calculation process will vary. The classifications for each system are listed in Table 6-79. Below, in Table 6-80, the quartile ranking for the CSI values under method 2 are displayed.

Table 6-79 System Classifications for Method 2

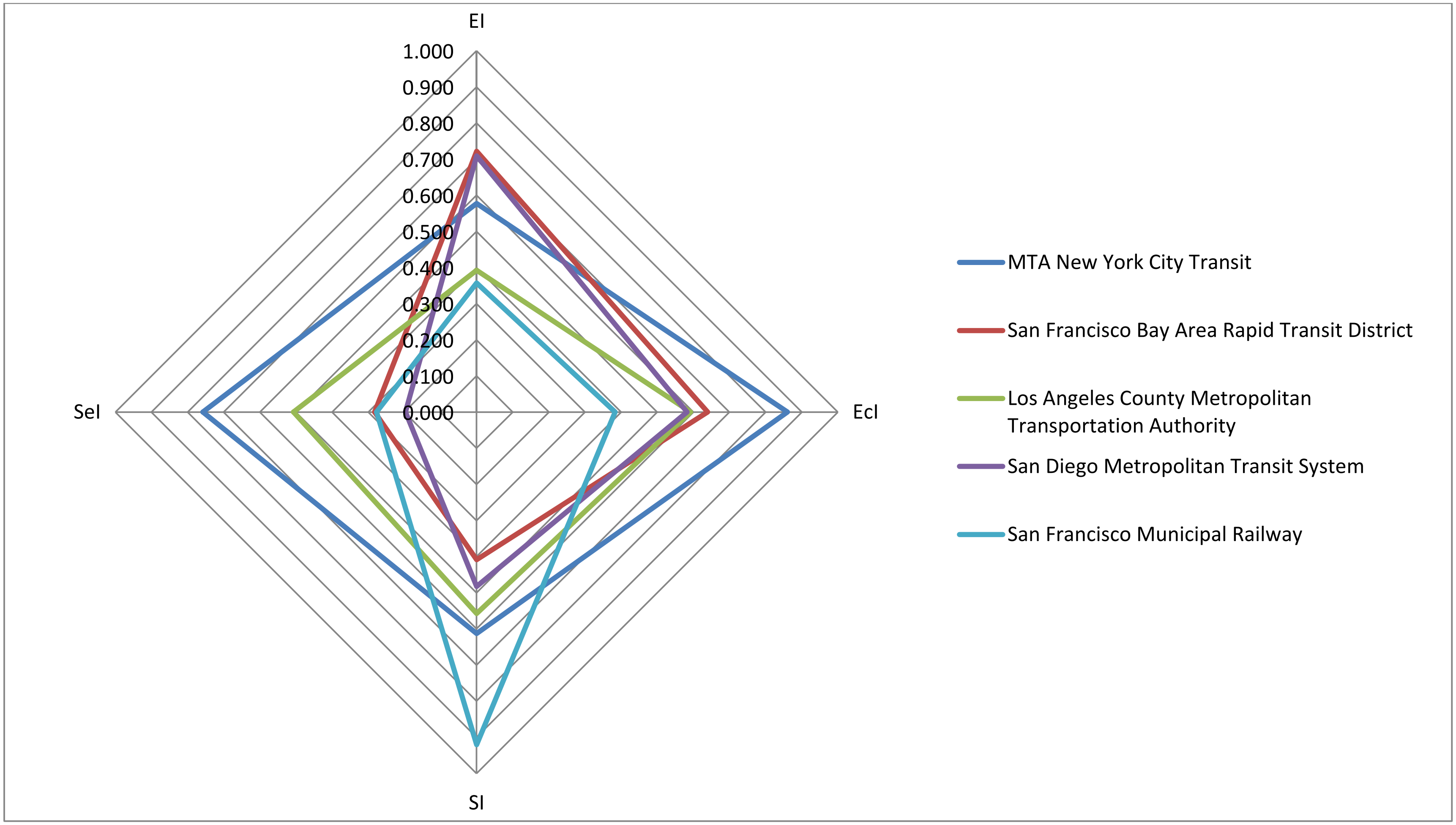
Operator Name	Mode	Classification
Metropolitan Atlanta Rapid Transit Authority	HR	Balanced Performance (High)
Los Angeles County Metropolitan Transportation Authority	HR	Balanced Performance (High)
Tri-County Metropolitan Transportation District of Oregon	LR	Balanced Performance (High)
Metropolitan Transit Authority of Harris County, Texas	LR	Balanced Performance (High)
Los Angeles County Metropolitan Transportation Authority	LR	Balanced Performance (High)
Massachusetts Bay Transportation Authority	LR	Balanced Performance (Medium)
Metro Transit	LR	Balanced Performance (Medium)
Sacramento Regional Transit District	LR	Balanced Performance (Medium)
Valley Metro Rail, Inc.	LR	Balanced Performance (Medium)
Port Authority Trans-Hudson Corporation	HR	Low Performance
Staten Island Rapid Transit Operating Authority	HR	Low Performance
Miami-Dade Transit	HR	Low Performance
The Greater Cleveland Regional Transit Authority	HR	Low Performance
Port Authority of Allegheny County	LR	Low Performance
Maryland Transit Administration	LR	Low Performance
Charlotte Area Transit System	LR	Low Performance
The Greater Cleveland Regional Transit Authority	LR	Low Performance
Dallas Area Rapid Transit	LR	Low Performance
Denver Regional Transportation District	LR	Low Performance
Massachusetts Bay Transportation Authority	HR	Specialized Performance
Southeastern Pennsylvania Transportation Authority	HR	Specialized Performance
Washington Metropolitan Area Transit Authority	HR	Specialized Performance
Maryland Transit Administration	HR	Specialized Performance
Chicago Transit Authority	HR	Specialized Performance
San Francisco Bay Area Rapid Transit District	HR	Specialized Performance
Central Puget Sound Regional Transit Authority	LR	Specialized Performance
Niagara Frontier Transportation Authority	LR	Specialized Performance
Bi-State Development Agency	LR	Specialized Performance
Utah Transit Authority	LR	Specialized Performance
Santa Clara Valley Transportation Authority	LR	Specialized Performance
San Francisco Municipal Railway	LR	Specialized Performance
San Diego Metropolitan Transit System	LR	Specialized Performance
MTA New York City Transit	HR	Superior Performance

Table 6-80 CSI Ranking for Method 2

Rank	Operator Name	Mode	CSI	Performance
1	MTA New York City Transit	HR	0.702	Highest
2	San Francisco Bay Area Rapid Transit District	HR	0.513	LR
3	Los Angeles County Metropolitan Transportation Authority	HR	0.512	5
4	San Diego Metropolitan Transit System	LR	0.493	HR
5	San Francisco Municipal Railway	LR	0.484	3
6	Los Angeles County Metropolitan Transportation Authority	LR	0.468	
7	Tri-County Metropolitan Transportation District of Oregon	LR	0.467	
8	Metropolitan Transit Authority of Harris County, Texas	LR	0.460	
9	Central Puget Sound Regional Transit Authority	LR	0.448	High
10	Metropolitan Atlanta Rapid Transit Authority	HR	0.432	LR
11	Chicago Transit Authority	HR	0.432	4
12	Washington Metropolitan Area Transit Authority	HR	0.418	HR
13	Southeastern Pennsylvania Transportation Authority	HR	0.413	5
14	Valley Metro Rail, Inc.	LR	0.392	
15	Massachusetts Bay Transportation Authority	HR	0.381	
16	Utah Transit Authority	LR	0.379	
17	Massachusetts Bay Transportation Authority	LR	0.373	
18	Port Authority Trans-Hudson Corporation	HR	0.373	Low
19	Niagara Frontier Transportation Authority	LR	0.368	LR
20	Sacramento Regional Transit District	LR	0.366	7
21	Metro Transit	LR	0.358	HR
22	Bi-State Development Agency	LR	0.357	2
23	Santa Clara Valley Transportation Authority	LR	0.354	
24	Denver Regional Transportation District	LR	0.325	
25	Maryland Transit Administration	HR	0.318	
26	Charlotte Area Transit System	LR	0.303	
27	Dallas Area Rapid Transit	LR	0.300	Poorest
28	Miami-Dade Transit	HR	0.297	LR
29	Maryland Transit Administration	LR	0.296	4
30	Staten Island Rapid Transit Operating Authority	HR	0.285	HR
31	The Greater Cleveland Regional Transit Authority	HR	0.265	3
32	Port Authority of Allegheny County	LR	0.256	
33	The Greater Cleveland Regional Transit Authority	LR	0.229	

The category index values for the top five systems are graphed in Figure 6-28.This technique along with the four category sustainability model, and utility method were all used by Jeon in her 2007 dissertation to outline the comparative benefits of different plan alternatives for the transport network in Atlanta. These techniques have now been applied to transit systems for composite sustainability analysis. As seen in the figure, some systems present balanced performance, while others have specialized performance, but aside from MTA New York, none of the top systems achieve strong scores in all categories. While New York is the top system in economic and system effectiveness, it does not achieve overall best performance across all categories.

Figure 6-28 Radar Diagram for Method 2



6.7.3 Method 3: Rescaling

A similar approach is utilized to classify and analyze results for method 3 as the past two methods.

Table 6-81 EI Ranking for Method 3

Rank	Operator Name	Mode	EI	Performance
1	San Francisco Bay Area Rapid Transit District	HR	0.979	Highest
2	MTA New York City Transit	HR	0.977	LR
3	San Diego Metropolitan Transit System	LR	0.977	5
4	Central Puget Sound Regional Transit Authority	LR	0.973	HR
5	Tri-County Metropolitan Transportation District of Oregon	LR	0.955	3
6	Los Angeles County Metropolitan Transportation Authority	LR	0.933	
7	Metropolitan Atlanta Rapid Transit Authority	HR	0.918	
8	Valley Metro Rail, Inc.	LR	0.913	
9	Port Authority Trans-Hudson Corporation	HR	0.905	High
10	Los Angeles County Metropolitan Transportation Authority	HR	0.887	LR
11	Metropolitan Transit Authority of Harris County, Texas	LR	0.868	6
12	San Francisco Municipal Railway	LR	0.868	HR
13	Sacramento Regional Transit District	LR	0.860	3
14	Santa Clara Valley Transportation Authority	LR	0.847	
15	Chicago Transit Authority	HR	0.840	
16	Massachusetts Bay Transportation Authority	LR	0.839	
17	Bi-State Development Agency	LR	0.825	
18	Metro Transit	LR	0.805	Low
19	Denver Regional Transportation District	LR	0.786	LR
20	Massachusetts Bay Transportation Authority	HR	0.784	5
21	Staten Island Rapid Transit Operating Authority, dba: MTA Staten Island Railway	HR	0.776	HR
22	Charlotte Area Transit System	LR	0.775	3

Rank	Operator Name	Mode	EI	Performance
23	Southeastern Pennsylvania Transportation Authority	HR	0.765	
24	Niagara Frontier Transportation Authority	LR	0.733	
25	Utah Transit Authority	LR	0.710	
26	Miami-Dade Transit	HR	0.661	Poorest
27	Dallas Area Rapid Transit	LR	0.658	LR
28	Washington Metropolitan Area Transit Authority	HR	0.620	4
29	Maryland Transit Administration	LR	0.503	HR
30	Maryland Transit Administration	HR	0.325	4
31	Port Authority of Allegheny County	LR	0.251	
32	The Greater Cleveland Regional Transit Authority	LR	0.195	
33	The Greater Cleveland Regional Transit Authority	HR	0.000	

Table 6-82 Eci Ranking for Method 3

Rank	Operator Name	Mode	Eci	Performance
1	MTA New York City Transit	HR	0.935	Highest
2	Washington Metropolitan Area Transit Authority	HR	0.717	LR
3	Southeastern Pennsylvania Transportation Authority	HR	0.690	1
4	Metropolitan Atlanta Rapid Transit Authority	HR	0.659	HR
5	Chicago Transit Authority	HR	0.653	7
6	Massachusetts Bay Transportation Authority	HR	0.652	
7	Los Angeles County Metropolitan Transportation Authority	HR	0.642	
8	Metropolitan Transit Authority of Harris County, Texas	LR	0.630	
9	San Diego Metropolitan Transit System	LR	0.623	High
10	San Francisco Bay Area Rapid Transit District	HR	0.594	LR
11	Utah Transit Authority	LR	0.583	7
12	Massachusetts Bay Transportation Authority	LR	0.548	HR
13	Sacramento Regional Transit District	LR	0.546	2
14	Tri-County Metropolitan Transportation District of Oregon	LR	0.545	
15	Bi-State Development Agency	LR	0.531	
16	Metro Transit	LR	0.530	
17	Miami-Dade Transit	HR	0.512	
18	Maryland Transit Administration	HR	0.510	Low
19	Los Angeles County Metropolitan Transportation Authority	LR	0.504	LR
20	Port Authority Trans-Hudson Corporation	HR	0.502	5
21	Denver Regional Transportation District	LR	0.481	HR
22	Staten Island Rapid Transit Operating Authority	HR	0.451	3
23	Valley Metro Rail, Inc.	LR	0.438	
24	Maryland Transit Administration	LR	0.426	
25	Charlotte Area Transit System	LR	0.417	
26	Central Puget Sound Regional Transit Authority	LR	0.389	Poorest
27	San Francisco Municipal Railway	LR	0.385	LR
28	Niagara Frontier Transportation Authority	LR	0.383	7
29	The Greater Cleveland Regional Transit Authority	HR	0.380	HR
30	The Greater Cleveland Regional Transit Authority	LR	0.356	1

Rank	Operator Name	Mode	EcI	Performance
31	Santa Clara Valley Transportation Authority	LR	0.353	
32	Dallas Area Rapid Transit	LR	0.351	
33	Port Authority of Allegheny County	LR	0.256	

Table 6-83 SI Ranking for Method 3

Rank	Operator Name	Mode	SI	Performance
1	San Francisco Municipal Railway	LR	0.948	Highest
2	Metropolitan Transit Authority of Harris County, Texas	LR	0.749	LR
3	Niagara Frontier Transportation Authority	LR	0.729	5
4	Maryland Transit Administration	HR	0.680	HR
5	Santa Clara Valley Transportation Authority	LR	0.676	3
6	MTA New York City Transit	HR	0.672	
7	Utah Transit Authority	LR	0.671	
8	Los Angeles County Metropolitan Transportation Authority	HR	0.663	
9	Massachusetts Bay Transportation Authority	HR	0.661	High
10	Tri-County Metropolitan Transportation District of Oregon	LR	0.658	LR
11	Metro Transit	LR	0.635	7
12	Metropolitan Atlanta Rapid Transit Authority	HR	0.624	HR
13	Maryland Transit Administration	LR	0.621	2
14	Sacramento Regional Transit District	LR	0.620	
15	Los Angeles County Metropolitan Transportation Authority	LR	0.618	
16	Charlotte Area Transit System	LR	0.614	
17	Port Authority of Allegheny County	LR	0.604	
18	Washington Metropolitan Area Transit Authority	HR	0.603	Low
19	Dallas Area Rapid Transit	LR	0.601	LR
20	Valley Metro Rail, Inc.	LR	0.592	6
21	San Diego Metropolitan Transit System	LR	0.592	HR
22	Denver Regional Transportation District	LR	0.585	2
23	Central Puget Sound Regional Transit Authority	LR	0.577	
24	Chicago Transit Authority	HR	0.566	
25	Massachusetts Bay Transportation Authority	LR	0.553	

Rank	Operator Name	Mode	SI	Performance
26	Miami-Dade Transit	HR	0.545	Poorest
27	Southeastern Pennsylvania Transportation Authority	HR	0.536	LR
28	Bi-State Development Agency	LR	0.526	2
29	Port Authority Trans-Hudson Corporation	HR	0.496	HR
30	The Greater Cleveland Regional Transit Authority	HR	0.458	6
31	Staten Island Rapid Transit Operating Authority, dba: MTA Staten Island Railway	HR	0.420	
32	The Greater Cleveland Regional Transit Authority	LR	0.345	
33	San Francisco Bay Area Rapid Transit District	HR	0.301	

Table 6-84 SeI Ranking for Method 3

	Operator Name	Mode	SeI	Performance
1	MTA New York City Transit	HR	0.685	Highest
2	Los Angeles County Metropolitan Transportation Authority	HR	0.505	LR
3	Chicago Transit Authority	HR	0.318	1
4	Los Angeles County Metropolitan Transportation Authority	LR	0.309	HR
5	Southeastern Pennsylvania Transportation Authority	HR	0.291	7
6	Port Authority Trans-Hudson Corporation	HR	0.241	
7	Washington Metropolitan Area Transit Authority	HR	0.228	
8	The Greater Cleveland Regional Transit Authority	HR	0.202	
9	Tri-County Metropolitan Transportation District of Oregon	LR	0.201	High
10	San Francisco Bay Area Rapid Transit District	HR	0.198	LR
11	San Francisco Municipal Railway	LR	0.177	8
12	Utah Transit Authority	LR	0.157	HR
13	Massachusetts Bay Transportation Authority	LR	0.141	1
14	Valley Metro Rail, Inc.	LR	0.139	
15	The Greater Cleveland Regional Transit Authority	LR	0.134	
16	Niagara Frontier Transportation Authority	LR	0.127	
17	Bi-State Development Agency	LR	0.115	
18	Dallas Area Rapid Transit	LR	0.103	Low
19	San Diego Metropolitan Transit System	LR	0.098	LR
20	Metro Transit	LR	0.095	5
21	Metropolitan Transit Authority of Harris County, Texas	LR	0.090	HR
22	Massachusetts Bay Transportation Authority	HR	0.076	3
23	Staten Island Rapid Transit Operating Authority, dba: MTA Staten Island Railway	HR	0.073	
24	Metropolitan Atlanta Rapid Transit Authority	HR	0.067	
25	Santa Clara Valley Transportation Authority	LR	0.066	

	Operator Name	Mode	Sel	Performance
26	Port Authority of Allegheny County	LR	0.045	Poorest
27	Denver Regional Transportation District	LR	0.045	LR
28	Miami-Dade Transit	HR	0.043	6
29	Maryland Transit Administration	LR	0.041	HR
30	Sacramento Regional Transit District	LR	0.033	2
31	Charlotte Area Transit System	LR	0.023	
32	Central Puget Sound Regional Transit Authority	LR	0.019	
33	Maryland Transit Administration	HR	0.009	

Similar to method 2, method 3 compares each system to the highest performer, rather than the average, in order to calculate the indices. There are some differences compared to method 1.

- In the environmental category, the general trend is for LR systems to achieve greater performance based on a criterion analyzing the highest and high performance categories. In the two highest categories, LR had 5 and 6 spots respectively.
- In the economic category, the highest category is populated with 7 HR systems and 1 LR system, indicating overall superior performance by HR for this category. Similar to the environmental category indicator, the high category has more LR than HR systems (7 to 2); however the performance levels are quite similar between all systems. This indicates that high performance LR systems perform at a similar level to middle level HR systems.
- In the social category, there are 6 LR and 2 HR in the highest performance category and 5 and 4 of each in the high category. This indicates a slight performance advantage by the LR systems, with high level HR systems competing with mid-level LR systems.
- In the system effectiveness category, 7 HR systems populate the highest category, compared to 1 LR, in the high category there are 8 LR and 1 HR – suggesting the highest performance LR systems in the USA achieve better results than the middle HR systems.

All systems have been categorized based on their categorical index results in Table 6-84.

Table 6-85 System Categories for Method 3

Operator Name	Mode	Classification
Massachusetts Bay Transportation Authority	HR	Balanced Performance (High)
MTA New York City Transit	HR	Superior Performance
Port Authority Trans-Hudson Corporation	HR	Balanced Performance (Medium)
Staten Island Rapid Transit Operating Authority	HR	Low Performance
Southeastern Pennsylvania Transportation Authority	HR	Specialized Performance
Washington Metropolitan Area Transit Authority	HR	Balanced Performance (High)
Maryland Transit Administration	HR	Specialized Performance
Metropolitan Atlanta Rapid Transit Authority	HR	Specialized Performance
Miami-Dade Transit	HR	Specialized Performance
The Greater Cleveland Regional Transit Authority	HR	Specialized Performance
Chicago Transit Authority	HR	Balanced Performance (High)
San Francisco Bay Area Rapid Transit District	HR	Specialized Performance
Los Angeles County Metropolitan Transportation Authority	HR	Balanced Performance (High)
Tri-County Metropolitan Transportation District of Oregon	LR	Balanced Performance (High)
Central Puget Sound Regional Transit Authority	LR	Specialized Performance
Massachusetts Bay Transportation Authority LR	LR	Balanced Performance (Medium)
Niagara Frontier Transportation Authority	LR	Specialized Performance
Port Authority of Allegheny County	LR	Specialized Performance
Maryland Transit Administration	LR	Low Performance
Charlotte Area Transit System	LR	Specialized Performance
The Greater Cleveland Regional Transit Authority	LR	Specialized Performance
Metro Transit	LR	Balanced Performance (Medium)
Metropolitan Transit Authority of Harris County, Texas	LR	Balanced Performance (High)
Dallas Area Rapid Transit	LR	Low Performance
Bi-State Development Agency	LR	Balanced Performance (High)
Utah Transit Authority	LR	Balanced Performance (High)
Denver Regional Transportation District	LR	Low Performance
Santa Clara Valley Transportation Authority	LR	Balanced Performance

Operator Name	Mode	Classification
		(Medium)
San Francisco Municipal Railway	LR	Balanced Performance (High)
Sacramento Regional Transit District	LR	Balanced Performance (High)
San Diego Metropolitan Transit System	LR	Balanced Performance (High)
Los Angeles County Metropolitan Transportation Authority	LR	Balanced Performance (High)
Valley Metro Rail, Inc.	LR	Specialized Performance

Finally, the CSI values for method 3 by performance quartile are shown in Table 6-86.

Table 6-86 CSI Ranking for Method 3

Rank	Operator Name	Mode	CSI	Performance
1	MTA New York City Transit	HR	0.817	Highest
2	Los Angeles County Metropolitan Transportation Authority	HR	0.674	LR
3	Chicago Transit Authority	HR	0.594	5
4	San Francisco Municipal Railway	LR	0.594	HR
5	Los Angeles County Metropolitan Transportation Authority	LR	0.591	3
6	Tri-County Metropolitan Transportation District of Oregon	LR	0.590	
7	Metropolitan Transit Authority of Harris County, Texas	LR	0.584	
8	San Diego Metropolitan Transit System	LR	0.572	
9	Southeastern Pennsylvania Transportation Authority	HR	0.571	High
10	Metropolitan Atlanta Rapid Transit Authority	HR	0.567	LR
11	Massachusetts Bay Transportation Authority	HR	0.543	3
12	Washington Metropolitan Area Transit Authority	HR	0.542	HR
13	Port Authority Trans-Hudson Corporation	HR	0.536	6
14	Utah Transit Authority	LR	0.530	
15	Valley Metro Rail, Inc.	LR	0.520	
16	Massachusetts Bay Transportation Authority	LR	0.520	
17	San Francisco Bay Area Rapid Transit District	HR	0.518	
18	Metro Transit	LR	0.516	Low
19	Sacramento Regional Transit District	LR	0.515	LR
20	Bi-State Development Agency	LR	0.499	8
21	Niagara Frontier Transportation Authority	LR	0.493	HR
22	Central Puget Sound Regional Transit Authority	LR	0.490	0
23	Santa Clara Valley Transportation Authority	LR	0.486	
24	Denver Regional Transportation District	LR	0.474	
25	Charlotte Area Transit System	LR	0.457	
26	Miami-Dade Transit	HR	0.440	Poorest
27	Staten Island Rapid Transit Operating Authority	HR	0.430	LR
28	Dallas Area Rapid Transit	LR	0.428	4
29	Maryland Transit Administration	LR	0.398	HR

Rank	Operator Name	Mode	CSI	Performance
30	Maryland Transit Administration	HR	0.381	4
31	Port Authority of Allegheny County	LR	0.289	
32	The Greater Cleveland Regional Transit Authority	HR	0.260	
33	The Greater Cleveland Regional Transit Authority	LR	0.257	

The CSI values shown in 6-86 highlight how systems from each mode set are able to achieve high or low performance. A strength of methods 2 and 3 is the clear range of values between 0-1 for normalized indicators. This strength has been put to use in a series of diagrams that are companion pieces to the CSI value. Data has been treated into multi-dimensional plots that show the relative strengths and weaknesses of a given transit system to add quick depth of analysis in companion to the CSI. The results of this data treatment and analysis are demonstrated with an alternative method in Figures 6-29 and 30.

Figure 6-29 Sustainability Graph for MTA New York

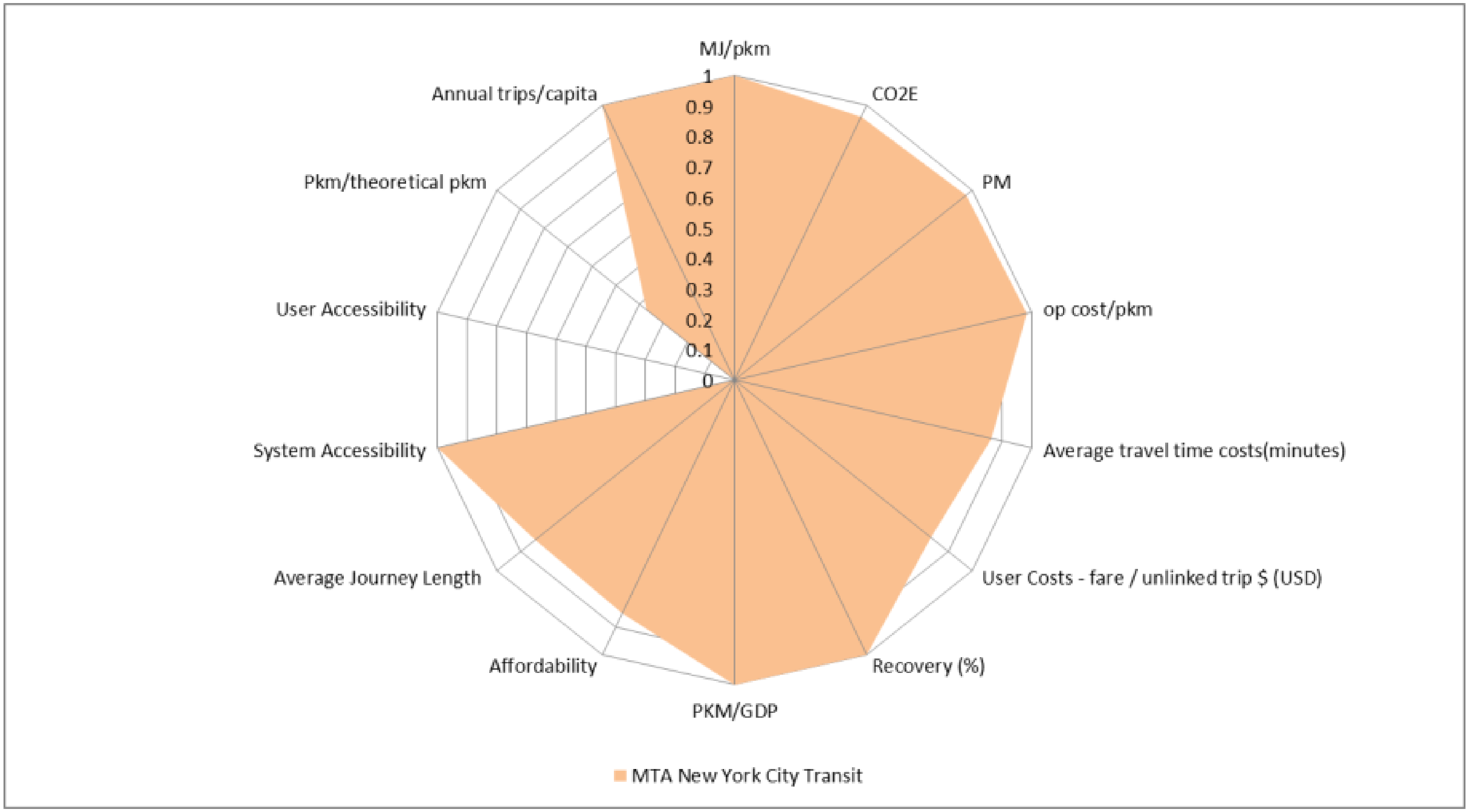
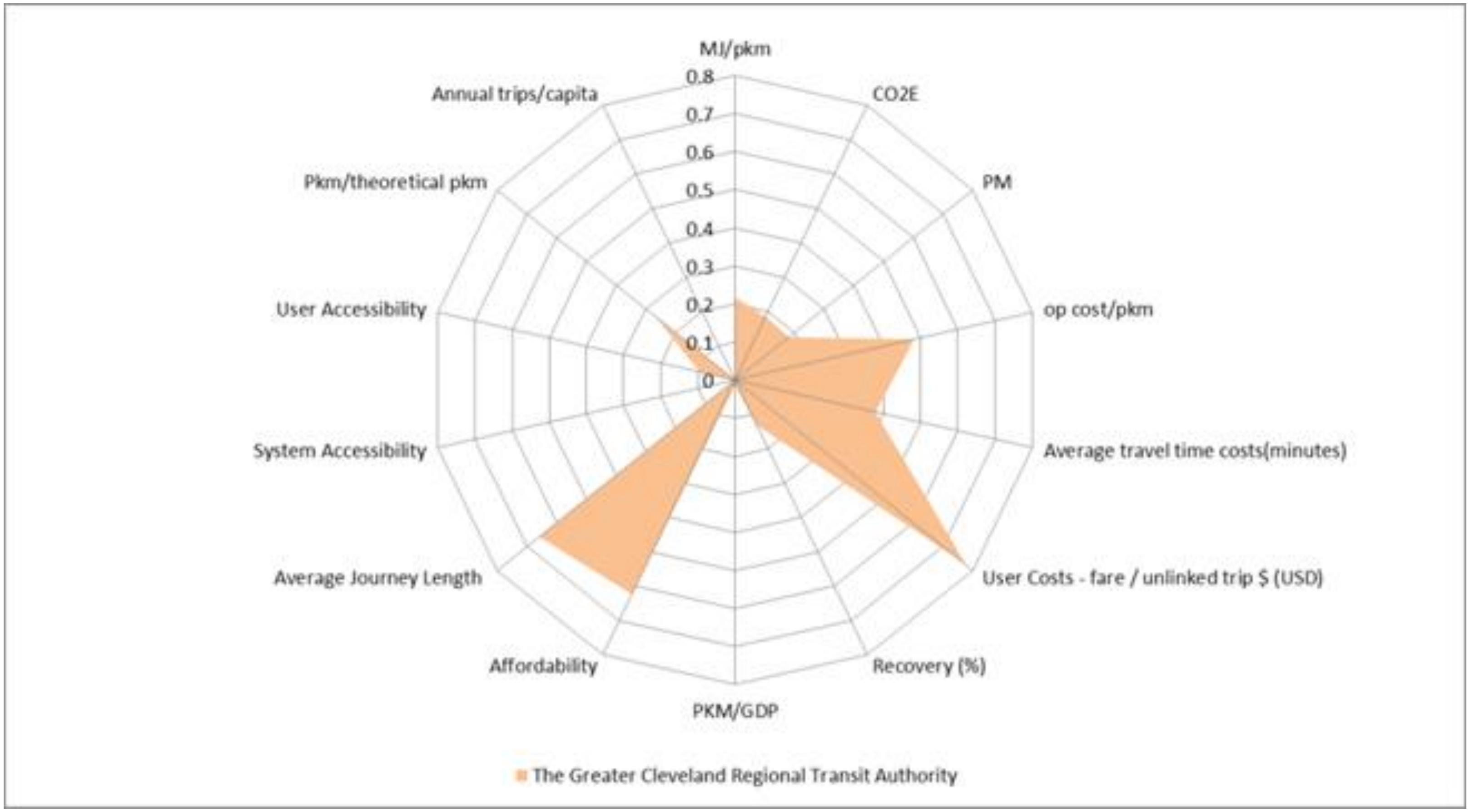


Figure 6-30 Sustainability Graph for the Greater Cleveland Regional Transit Authority (LR)



New York MTA – has the highest CSI and is the top performer in several factors. However, it still scores a zero in one area – it is the loser in user accessibility. The Greater Cleveland Regional Transit Authority is the lowest scoring system in many factors and lowest overall. These two diagrams highlight an important point of discussion as they enable the CSI value to be viewed without weighting in an 'exploded form'. While the CSI attempts to synthesize the different dimensions of sustainability into a clear characteristic, these graphs are an essential companion piece that enables quick contextualization behind the scores received by a given system. A complete set of these figures is contained in Appendix D.

6.7.4 Comparison of Methods for assessing Sustainability Performance - potential biases in interpretation

The overall trends of which systems are represented in each performance quartile do not differ between methodologies. Populations may shift by 1 between methodologies. However, there is a difference between the rankings that each system receives. Again, as this method is based on the highest performer, rather than the mean, the values a system receives in the calculation process will vary.

However, there is disparity between the methods for how systems are classified. The classifications for each system are listed in Table 6-87.

Table 6-87 Comparison of Classifications Between CSI Methods

	Method 1	Method 2	Method 3
Balanced Performance (High)	11	5	12
Balanced Performance (Medium)	3	4	4
Low Performance	9	10	4
Specialized Performance	9	13	12
Superior Performance	1	1	1

For CSI values, the quantities of systems represented in the top two performance tiers are different for method 2 than method 1. While method 1 had equal representation of LR and HR in the highest tier, and 5 LR and 4 HR in the high tier, method 2 has 5 LR and 3 HR in the highest tier, and 4 LR and 5 HR in the high tier. Method 3 has the same representation as method 1. For the bottom two tiers the populations are the same.

Method 2 and 3 calculations produced a greater number of specialized systems and fewer high performance systems. Medium and Low performance system populations were nearly equal size in both methods. In all methods only MTA New York City Transit achieved superior performance. A total of 11 systems changed classification between methodologies. These differences occur due to the nature of how indices are calculated – normalization varies between methods.

In method 1, systems can have negative values associated with low performance, while in method 2 they just have a lower positive value. Further, in method 1, there are signs attached to individual weights – negative signs to factors that should be minimized and positive to signs that should be maximized, while in method 2 all signs are positive. As a result, poor performance can count against high performance in method 1, whereas in method 2 all performance is additive. This explains the discrepancy between models. This can also be explained using a thought experiment – imagine two systems, i and j, for category index x which has three factors: a, b, and c. For i factors a and b are middle performers, while c is low. For j, factor a is a high performer, while b and c are both very low performers.

- Under method 1, for i factors a and b are low above zero values, while c is a negative value. Upon summing the index for I is a low positive. For j, upon summing, the factor is zero due to the negative values calculated for b and c.
    - Despite the superior performance under factor a, j still has a lower category index.
- However, under method 2, for both systems all factors are above zero. As 1 is the maximum and 0 is the minimum value, depending on the performance of j, it can sum up to be greater than i in this scenario.

- Further, in method 3, a system in each set for each indicator will receive a zero score and a 1 score – meaning the minimum score is lower than method 2, but still constrained between 0-1.
- Whether or not there is a difference between the methods is based on whether performance is uniform across all factors in a category (i.e. all factors are above zero in method 1).

The sustainability performance measured by the three methodologies results in a clear ranking system that enables further research into particular sustainable transportation system issues. It also emphasizes the notion that strong performance across all 14 factors considered in this study is possible regardless of mode – indicating further research in this field is required that analyzes the intersection of operations, design, and planning along with urban factors. What factors shape and influence poor or strong performance? These issues need further exploration.

Continuing from the previous discussion it is important to note that the ranking system developed in this tool attempts to aggregate indicators to inform understanding of a transit system's sustainability. However, high scoring systems often do have at least one indicator with poor performance. MTA New York, for example, receives a zero in User Accessibility under method 3, and the lowest scores under the other two methods because it has the least number of stations that are ADA compliant. However, in all three methods it has the highest score overall. This underscores the need for both the holistic look at sustainability along with the nuanced multidimensional look provided by all three methods.

6.8 Sensitivity Analysis and Discussion

6.8.1 Sensitivity Analysis

A limitation of this study is that it does not present a complete application of MCA techniques – base weighting values have been applied for analysis factors and indices in order to calculate a composite sustainability index and comment on sustainability across different modes or transit technologies, however these weightings did not have rigorous analysis, such as consultation or an analytical hierarchical process imbedded within them. In order to expand this study beyond this limitation, the following sub section presents a sensitivity analysis. This sensitivity analysis incorporated new index weights in a total of 12 new tests which comment on how the CSI scores for each system may shift based on how different priorities are placed on different sustainability indexes.

In the original analysis formulation, each weight was set to a value of 0.25 and all four weights were set to sum to 1. In this set of tests, the four weights must still sum to 1, however, in each test one of the weights is increased above 0.25 and the difference is split evenly among the other three weights. Each weight has three tests – one with an increase of 0.05, an increase of 0.1, and finally an increase of 0.15.

These tests are thought to reflect three elements previously missing from this research in that they:

- Provide insight into how a more nuanced approach to weighting, such as the application of an analytical hierarchical process or other in depth MCA technique, may inform future research into sustainable mobility and mass transit with the application of CSI tools
- Comment on how diverse views on sustainability and various goals within public transit system operation and service provision, planning and development, as well as debate in sustainability analysis itself, all of which can shape the implementation of public transit systems, can be applied within this research framework. For example, a strong value placed on reducing greenhouse gasses may be reflected in a heavy environmental weighting that may lead to systems that are more cost effective but less environmentally sound performing lower in a CSI framework.
- Compute additional CSI values demonstrating further application of the framework and techniques.

The tests are formulated as follows:

Recalling that $w_e + w_s + w_n + w_y = 1$

Test	Increased Value	Decreased Values	Description
Test 1 Test 2 Test 3	$w_e = 0.3$ $w_e = 0.35$ $w_e = 0.40$	$w_s = w_n = w_y = 0.2333$ $w_s = w_n = w_y = 0.2167$ $w_s = w_n = w_y = 0.2$	Heavier weight put on environmental factors. Example – strongest emphasis is put on environmental policy to limit emissions and greenhouse gases.
Test 4 Test 5 Test 6	$w_n = 0.3$ $w_n = 0.35$ $w_n = 0.40$	$w_s = w_e = w_y = 0.2333$ $w_s = w_e = w_y = 0.2167$ $w_s = w_e = w_y = 0.2$	Heavier weight put on economic factors. Example – strongest emphasis is put on economic policy to run a cost effective system.
Test 7 Test 8 Test 9	$w_s = 0.3$ $w_s = 0.35$ $w_s = 0.40$	$w_n = w_e = w_y = 0.2333$ $w_n = w_e = w_y = 0.2167$ $w_n = w_e = w_y = 0.2$	Heavier weight put on social factors. Example – strongest emphasis is put on social policy develop an inclusive system with social benefits.
Test 10 Test 11 Test 12	$w_y = 0.3$ $w_y = 0.35$ $w_y = 0.40$	$w_n = w_e = w_s = 0.2333$ $w_n = w_e = w_s = 0.2167$ $w_n = w_e = w_s = 0.2$	Heavier weight put on system effectiveness factors. Example – strongest emphasis is put on running a high capacity system at peak effectiveness.

The first set of sensitivity tests are for the z-score method (method 1) in Table 6-88, Table 6-89, Table 6-90, and Table 6-91, followed by analysis. The following colour scheme is used to represent HR and LR systems:

HR
LR

Table 6-88 Environmental Sensitivity for Method 1

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	1.5727	New York	1.528	-2.84%	New York	1.4833	-5.69%	New York	1.439	-8.53%
2	Los Angeles	0.7406	Los Angeles	0.7277	-1.75%	Los Angeles	0.7147	-3.51%	Los Angeles	0.702	-5.26%
3	San Francisco	0.445	San Francisco	0.4465	0.34%	San Francisco	0.448	0.68%	San Francisco	0.449	1.01%
4	Chicago	0.3852	Los Angeles	0.3894	6.58%	Los Angeles	0.4134	13.16%	Portland	0.44	27.10%
5	Los Angeles	0.3654	Chicago	0.3833	-0.50%	Portland	0.4087	18.07%	Los Angeles	0.437	19.74%
6	Portland	0.3461	Portland	0.3774	9.03%	Chicago	0.3814	-1.00%	Chicago	0.379	-1.50%
7	Houston	0.3412	Houston	0.3492	2.35%	Houston	0.3572	4.69%	Houston	0.365	7.04%
8	Philadelphia	0.3352	Philadelphia	0.3173	-5.35%	San Diego	0.3009	44.13%	San Diego	0.347	66.19%
9	Atlanta	0.2232	San Diego	0.2548	22.06%	Philadelphia	0.2993	-10.70%	Atlanta	0.311	39.44%
10	Washington	0.219	Atlanta	0.2525	13.15%	Atlanta	0.2819	26.29%	Philadelphia	0.281	-16.05%
11	San Diego	0.2088	Washington	0.1912	-12.70%	Jersey City	0.2109	42.22%	Jersey City	0.242	63.33%
12	Boston	0.1512	Jersey City	0.1796	21.11%	Washington	0.1634	-25.41%	Boston	0.148	49.56%
13	Jersey City	0.1483	Boston	0.1496	-1.05%	Boston	0.148	-2.11%	Boston	0.146	-3.16%
14	Boston	0.099	Boston	0.115	16.52%	Boston	0.131	33.04%	Phoenix	0.14	746.04%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
		1		5			8			1	
15	Salt Lake City	0.0909	Salt Lake City	0.0717	-21.09%	Phoenix	0.0995	497.36%	Washington	0.136	-38.11%
16	Phoenix	0.0167	Phoenix	0.0581	248.68%	Sacramento	0.0587	13031.90%	Sacramento	0.088	19547.85%
17	Sacramento	0.0004	Sacramento	0.0296	6515.95%	Salt Lake City	0.0525	-42.18%	Seattle	0.069	150.54%
19	Minneapolis	1E-05	Minneapolis	0.0137	118169.15%	Minneapolis	0.0274	236338%	Oakland	0.054	133.88%
20	Buffalo	-0.008	Buffalo	-0.012	-49.79%	Seattle	0.0005	100.36%	Minneapolis	0.041	354507%
21	San Jose	-0.082	San Jose	-0.051	38.12%	Buffalo	-0.0159	-99.58%	Salt Lake City	0.033	-63.27%
23	St. Louis	-0.093	St. Louis	-0.068	27.28%	Oakland	-0.0171	89.26%	San Jose	0.012	114.37%
24	Seattle	-0.136	Seattle	-0.068	50.18%	San Jose	-0.0195	76.24%	St. Louis	-0.017	81.83%
25	Oakland	-0.159	Oakland	-0.088	44.63%	St. Louis	-0.0425	54.55%	Buffalo	-0.02	-149.37%
26	Denver	-0.193	Denver	-0.172	10.79%	Denver	-0.1516	21.58%	Denver	-0.131	32.36%
27	Charlotte	-0.238	Charlotte	-0.216	9.34%	Charlotte	-0.1938	18.68%	Charlotte	-0.172	28.02%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
28	New York	-0.255	New York	-0.231	9.39%	New York	-0.2068	18.77%	New York	-0.183	28.16%
29	Miami	-0.33	Miami	-0.333	-0.90%	Miami	-0.3358	-1.79%	Miami	-0.339	-2.69%
30	Dallas	-0.335	Dallas	-0.338	-0.83%	Dallas	-0.3406	-1.67%	Dallas	-0.343	-2.50%
31	Baltimore	-0.461	Baltimore	-0.496	-7.48%	Baltimore	-0.5302	-14.97%	Baltimore	-0.565	-22.45%
32	Baltimore	-0.5	Baltimore	-0.579	-15.82%	Baltimore	-0.6581	-31.65%	Baltimore	-0.737	-47.47%
33	Pittsburgh	-0.901	Pittsburgh	-0.972	-7.87%	Pittsburgh	-1.0434	-15.75%	Pittsburgh	-1.114	-23.62%
34	Cleveland	-0.991	Cleveland	-1.073	-8.28%	Cleveland	-1.1556	-16.57%	Cleveland	-1.238	-24.85%
35	Cleveland	-1.005	Cleveland	-1.138	-13.24%	Cleveland	-1.2706	-26.47%	Cleveland	-1.404	-39.71%

Table 6-89 Economic Index Weighting Sensitivity Analysis for Method 1

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
1	New York	1.5727	New York	1.586	0.850%	New York	1.599	1.700%	New York	1.613	2.55%
2	Los Angeles	0.7406	Los Angeles	0.725	-2.073%	Los Angeles	0.710	-4.145%	Los Angeles	0.695	-6.22%
3	San Francisco	0.4450	Chicago	0.392	1.851%	Chicago	0.399	3.702%	Chicago	0.407	5.55%
4	Chicago	0.3852	San Francisco	0.385	-13.589%	Philadelphia	0.381	13.720%	Philadelphia	0.404	20.58%
5	Los Angeles	0.3654	Philadelphia	0.358	6.860%	Houston	0.363	6.383%	Houston	0.374	9.57%
6	Portland	0.3461	Houston	0.352	3.191%	San Francisco	0.324	-27.178%	Washington	0.319	45.85%
7	Houston	0.3412	Los Angeles	0.340	-7.061%	Portland	0.314	-9.197%	Atlanta	0.300	34.25%
8	Philadelphia	0.3352	Portland	0.330	-4.599%	Los Angeles	0.314	-14.122%	Portland	0.298	-13.80%
9	Atlanta	0.2232	Washington	0.252	15.284%	Washington	0.286	30.569%	Los Angeles	0.288	-21.18%
10	Washington	0.2190	Atlanta	0.249	11.415%	Atlanta	0.274	22.831%	San Francisco	0.264	-40.77%
11	San Diego	0.2088	San Diego	0.218	4.187%	San Diego	0.226	8.374%	San Diego	0.235	12.56%
12	Boston	0.1512	Boston	0.176	16.625%	Boston	0.201	33.249%	Boston	0.227	49.87%
13	Jersey City	0.1483	Jersey City	0.132	-11.103%	Jersey City	0.115	-22.206%	Salt Lake City	0.126	38.39%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
14	Boston	0.0991	Salt Lake City	0.102	12.796%	Salt Lake City	0.114	25.592%	Jersey City	0.099	-33.31%
15	Salt Lake City	0.0909	Boston	0.099	-0.105%	Boston	0.099	-0.210%	Boston	0.099	-0.32%
16	Phoenix	0.0167	Sacramento	0.008	1693.558%	Sacramento	0.016	3387.115%	Sacramento	0.023	5080.67%
17	Sacramento	0.0004	Minneapolis	-0.001	-6560.956%	Minneapolis	-0.002	-13121.911%	Minneapolis	-0.002	-19682.87%
19	Minneapolis	0.0000	Phoenix	-0.009	-155.865%	Phoenix	-0.035	-311.731%	Phoenix	-0.061	-467.60%
20	Buffalo	-0.0080	Buffalo	-0.036	-353.471%	Buffalo	-0.064	-706.943%	St. Louis	-0.074	21.26%
21	San Jose	-0.0821	St. Louis	-0.087	7.085%	St. Louis	-0.080	14.171%	Buffalo	-0.092	-1060.41%
23	St. Louis	-0.0935	San Jose	-0.118	-43.708%	Oakland	-0.142	10.754%	Oakland	-0.134	16.13%
24	Seattle	-0.1365	Oakland	-0.151	5.377%	San Jose	-0.154	-87.416%	San Jose	-0.190	-131.12%
25	Oakland	-0.1593	Seattle	-0.166	-21.744%	Denver	-0.195	-0.686%	Denver	-0.195	-1.03%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
26	Denver	-0.1933	Denver	-0.194	-0.343%	Seattle	-0.196	-43.487%	Seattle	-0.226	-65.23%
27	Charlotte	-0.2383	Charlotte	-0.249	-4.330%	New York	-0.253	0.671%	New York	-0.252	1.01%
28	New York	-0.2546	New York	-0.254	0.335%	Charlotte	-0.259	-8.659%	Charlotte	-0.269	-12.99%
29	Miami	-0.3299	Miami	-0.310	6.105%	Miami	-0.290	12.209%	Miami	-0.269	18.31%
30	Dallas	-0.3350	Dallas	-0.356	-6.186%	Dallas	-0.376	-12.373%	Baltimore	-0.393	21.44%
31	Baltimore	-0.4612	Baltimore	-0.454	1.506%	Baltimore	-0.428	14.293%	Dallas	-0.397	-18.56%
32	Baltimore	-0.4999	Baltimore	-0.464	7.146%	Baltimore	-0.447	3.012%	Baltimore	-0.440	4.52%
33	Pittsburgh	-0.9014	Pittsburgh	-0.910	-0.953%	Pittsburgh	-0.919	-1.906%	Cleveland	-0.918	8.59%
34	Cleveland	-0.9913	Cleveland	-0.971	2.098%	Cleveland	-0.947	5.724%	Pittsburgh	-0.927	-2.86%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
35	Cleveland	-1.0047	Cleveland	-0.976	2.862%	Cleveland	-0.950	4.197%	Cleveland	-0.929	6.29%

Table 6-90 Social Index Weighting Sensitivity Test for Method 1

	Base Case		**0.3**			**0.35**			**0.4**		
Rank	**City**	**CSI**	**City**	**CSI**	**% change from base**	**City**	**CSI**	**% change from base**	**City**	**CSI**	**% change from base**
1	New York	1.573	New York	1.511	-3.90%	New York	1.450	-7.80%	New York	1.389	-11.70%
2	Los Angeles	0.741	Los Angeles	0.710	-4.18%	Los Angeles	0.679	-8.35%	San Francisco	0.677	52.22%
3	San Francisco	0.445	San Francisco	0.522	17.41%	San Francisco	0.600	34.81%	Los Angeles	0.648	-12.53%
4	Chicago	0.385	Houston	0.367	7.69%	Houston	0.394	15.37%	Houston	0.420	23.06%
5	Los Angeles	0.365	Chicago	0.354	-8.17%	Portland	0.331	-4.41%	Portland	0.323	-6.61%
6	Portland	0.346	Los Angeles	0.345	-5.69%	Los Angeles	0.324	-11.38%	Los Angeles	0.303	-17.07%
7	Houston	0.341	Portland	0.338	-2.20%	Chicago	0.322	-16.34%	Chicago	0.291	-24.51%
8	Philadelphia	0.335	Philadelphia	0.310	-7.55%	Philadelphia	0.285	-15.11%	Philadelphia	0.259	-22.66%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
9	Atlanta	0.223	Atlanta	0.213	-4.55%	Atlanta	0.203	-9.09%	Atlanta	0.193	-13.64%
10	Washington	0.219	Washington	0.199	-9.07%	Washington	0.179	-18.15%	Boston	0.181	20.00%
11	San Diego	0.209	San Diego	0.187	-10.37%	Boston	0.171	13.33%	Washington	0.159	-27.22%
12	Boston	0.151	Boston	0.161	6.67%	San Diego	0.165	-20.73%	San Diego	0.144	-31.10%
13	Jersey City	0.148	Jersey City	0.117	-20.89%	Salt Lake City	0.118	29.79%	Salt Lake City	0.131	44.69%
14	Boston	0.099	Salt Lake City	0.104	14.90%	Boston	0.090	-9.16%	Buffalo	0.113	1518.04%
15	Salt Lake City	0.091	Boston	0.095	-4.58%	Jersey City	0.086	-41.77%	Boston	0.085	-13.74%
16	Phoenix	0.017	Buffalo	0.032	506.01%	Buffalo	0.073	1012.02%	Jersey City	0.055	-62.66%
17	Sacramento	0.000	Phoenix	0.009	-44.82%	Minneapolis	0.016	139152.97%	Minneapolis	0.024	208729.45%
19	Minneapolis	0.000	Minneapolis	0.008	69576.48%	Sacramento	0.006	1352.42%	Sacramento	0.010	2028.63%
20	Buffalo	-0.008	Sacramento	0.003	676.21%	Phoenix	0.002	-89.65%	San Jose	0.004	104.98%
21	San Jose	-0.082	San Jose	-0.053	34.99%	San Jose	-0.025	69.99%	Phoenix	-0.006	-134.47%
23	St. Louis	-	St. Louis	-	-25.94%	St. Louis	-	-51.87%	Seattle	-	-9.08%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
		0.093		0.118			0.142			0.149	
24	Seattle	-0.136	Seattle	-0.141	-3.03%	Seattle	-0.145	-6.05%	St. Louis	-0.166	-77.81%
25	Oakland	-0.159	Denver	-0.190	1.55%	Denver	-0.187	3.09%	Denver	-0.184	4.64%
26	Denver	-0.193	Charlotte	-0.222	6.67%	Charlotte	-0.206	13.35%	Charlotte	-0.191	20.02%
27	Charlotte	-0.238	Oakland	-0.265	-66.01%	New York	-0.285	-12.09%	Dallas	-0.277	17.40%
28	New York	-0.255	New York	-0.270	-6.04%	Dallas	-0.296	11.60%	New York	-0.301	-18.13%
29	Miami	-0.330	Dallas	-0.316	5.80%	Miami	-0.334	-1.15%	Baltimore	-0.327	34.68%
30	Dallas	-0.335	Miami	-0.332	-0.57%	Oakland	-0.370	-132.01%	Miami	-0.336	-1.72%
31	Baltimore	-0.461	Baltimore	-0.426	7.53%	Baltimore	-0.384	23.12%	Baltimore	-0.357	22.59%
32	Baltimore	-	Baltimore	-	11.56%	Baltimore	-	15.06%	Oakland	-	-198.02%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
		0.500		0.442			0.392			0.475	
33	Pittsburgh	-0.901	Pittsburgh	-0.845	6.22%	Pittsburgh	-0.789	12.45%	Pittsburgh	-0.733	18.67%
34	Cleveland	-0.991	Cleveland	-0.980	2.44%	Cleveland	-0.956	4.88%	Cleveland	-0.931	7.32%
35	Cleveland	-1.005	Cleveland	-0.987	0.42%	Cleveland	-0.983	0.84%	Cleveland	-0.979	1.26%

Table 6-91 System Effectiveness Weighting Sensitivity Analysis for Method 1

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
1	New York	1.573	New York	1.665	5.90%	New York	1.758	11.79%	New York	1.851	17.69%
2	Los Angeles	0.741	Los Angeles	0.800	8.00%	Los Angeles	0.859	16.01%	Los Angeles	0.918	24.01%
3	San Francisco	0.445	San Francisco	0.426	-4.16%	Chicago	0.438	13.64%	Chicago	0.464	20.46%
4	Chicago	0.385	Chicago	0.412	6.82%	Los Angeles	0.410	12.34%	Los Angeles	0.433	18.51%
5	Los Angeles	0.365	Los Angeles	0.388	6.17%	San Francisco	0.408	-8.31%	Philadelphia	0.396	18.13%
6	Portland	0.346	Philadelphia	0.355	6.04%	Philadelphia	0.376	12.09%	San Francisco	0.390	-12.47%
7	Houston	0.341	Portland	0.338	-2.23%	Portland	0.331	-4.46%	Portland	0.323	-6.69%
8	Philadelphia	0.335	Houston	0.296	-13.22%	Houston	0.251	-26.45%	Washington	0.262	19.48%
9	Atlanta	0.223	Washington	0.233	6.49%	Washington	0.247	12.99%	Houston	0.206	-39.67%
10	Washington	0.219	Atlanta	0.179	-20.01%	Jersey City	0.181	21.76%	Jersey City	0.197	32.64%
11	San Diego	0.209	San Diego	0.176	-15.88%	San Diego	0.142	-31.77%	San Diego	0.109	-47.65%
12	Boston	0.151	Jersey City	0.164	10.88%	Atlanta	0.134	-40.03%	Atlanta	0.089	-60.04%
13	Jersey City	0.148	Boston	0.118	-22.24%	Boston	0.084	-44.47%	Salt Lake City	0.073	-19.80%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
14	Boston	0.099	Boston	0.087	-11.83%	Salt Lake City	0.079	-13.20%	Boston	0.064	-35.50%
15	Salt Lake City	0.091	Salt Lake City	0.085	-6.60%	Boston	0.076	-23.67%	Boston	0.050	-66.71%
16	Phoenix	0.017	Phoenix	0.009	-47.99%	Phoenix	0.001	-95.98%	Phoenix	-0.007	-143.97%
17	Sacramento	0.000	Buffalo	-0.016	-102.75%	Buffalo	-0.024	-205.50%	Buffalo	-0.032	-308.25%
19	Minneapolis	0.000	Minneapolis	-0.021	-181184.67%	Minneapolis	-0.042	-362369.35%	Minneapolis	-0.063	-543554.02%
20	Buffalo	-0.008	Sacramento	-0.039	-8885.72%	Sacramento	-0.079	-17771.43%	Oakland	-0.083	48.00%
21	San Jose	-0.082	St. Louis	-0.101	-8.42%	Oakland	-0.108	32.00%	St. Louis	-0.117	-25.27%
23	St. Louis	-0.093	San Jose	-0.106	-29.41%	St. Louis	-0.109	-16.85%	Sacramento	-0.119	-26657.15%
24	Seattle	-0.136	Oakland	-0.134	16.00%	San Jose	-0.130	-58.82%	San Jose	-0.155	-88.22%
25	Oakland	-0.159	Seattle	-0.171	-25.41%	Seattle	-0.206	-50.82%	Seattle	-0.241	-76.24%
26	Denver	-0.193	Denver	-0.216	-11.99%	Denver	-0.240	-23.98%	Denver	-0.263	-35.98%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change from base	City	CSI	% change from base	City	CSI	% change from base
27	Charlotte	-0.238	New York	-0.264	-3.68%	New York	-0.273	-7.36%	New York	-0.283	-11.04%
28	New York	-0.255	Charlotte	-0.266	-11.68%	Charlotte	-0.294	-23.37%	Charlotte	-0.322	-35.05%
29	Miami	-0.330	Dallas	-0.331	1.22%	Dallas	-0.327	2.44%	Dallas	-0.323	3.66%
30	Dallas	-0.335	Miami	-0.345	-4.63%	Miami	-0.360	-9.27%	Miami	-0.376	-13.90%
31	Baltimore	-0.461	Baltimore	-0.468	-1.55%	Baltimore	-0.475	-3.10%	Baltimore	-0.483	-4.65%
32	Baltimore	-0.500	Baltimore	-0.514	-2.88%	Baltimore	-0.529	-5.76%	Baltimore	-0.543	-8.65%
33	Pittsburgh	-0.901	Pittsburgh	-0.878	2.60%	Cleveland	-0.845	15.86%	Cleveland	-0.766	23.80%
34	Cleveland	-0.991	Cleveland	-0.925	7.93%	Pittsburgh	-0.854	5.21%	Cleveland	-0.820	17.30%
35	Cleveland	-1.005	Cleveland	-0.934	5.77%	Cleveland	-0.877	11.53%	Pittsburgh	-0.831	7.81%

From the environmental sensitivity test, it can be observed that as the environmental weighting increased, the general performance of LR systems improved based on the population of LR systems in the highest performance tier. Out of the top 8 systems, originally 4 were LR under base weighting, under adjusted weighting of .35 and .4 for the environmental weight, 5 of the top systems were LR. However, not all LR systems improved performance. Alternatively, high performing HR systems improved their results with percent increases. From this result, it can be inferred that for the highest performing LR systems in the NTD dataset, an environmental weighting is advantageous based on their general higher environmental performance.

For the economic sensitivity test, as the weighting increased the population of LR systems in the top category dropped from 4, to 2 by the .40 weighting value. There was no change in population prior to this point, however the relative scoring of the LR systems dropped by .35 so the top four systems were all HR. These findings are in line with the general trend for higher economic performance for HR systems in the highest performance tiers.

For the social sensitivity test, the relative populations in the top 8 sustainable systems do not change. However, the rankings do change with an LR system, San Francisco Municipal Railway taking the second ranking spot, and the 4,5,6 spots also being taken by LR as opposed to the 3, 5,6,7. This would indicate that there is not as large a performance gap between LR and HR for this category, however, LR still has generally better performance.

For the system effectiveness set of indicators the LR population changes by one, dropping to three systems. For this test, some LR systems achieve greater performance for their CSI value as the weighing for system performance increases. The majority of top HR systems improve their results as well. This indicates that there is only a small performance advantage for HR systems for this indicator.

Table 6-92, Table 6-93, Table 6-94, and Table 6-95 display sensitivity results for method 2. Table 6-96, Table 6-97, Table 6-98, and Table 6-99 show the results for method 3.

Table 6-92 Environmental Sensitivity Test for Method 2

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.702	New York	0.694	-1.18%	New York	0.685	-2.37%	New York	0.677	-3.55%
2	Oakland	0.513	Oakland	0.527	2.72%	Oakland	0.541	5.44%	Oakland	0.555	8.15%
3	Los Angeles	0.512	San Diego	0.507	2.93%	San Diego	0.522	5.86%	San Diego	0.536	8.79%
4	San Diego	0.493	Los Angeles	0.504	-1.56%	Seattle	0.499	11.49%	Seattle	0.525	17.24%
5	San Francisco	0.484	San Francisco	0.476	-1.75%	Los Angeles	0.496	-3.12%	Los Angeles	0.488	-4.68%
6	Los Angeles	0.468	Seattle	0.473	5.75%	Portland	0.479	2.45%	Portland	0.485	3.68%
7	Portland	0.467	Portland	0.473	1.23%	Los Angeles	0.473	1.14%	Los Angeles	0.476	1.71%
8	Houston	0.460	Los Angeles	0.471	0.57%	San Francisco	0.467	-3.50%	San Francisco	0.459	-5.25%
9	Seattle	0.448	Houston	0.449	-2.26%	Houston	0.439	-4.51%	Atlanta	0.429	-0.71%
10	Atlanta	0.432	Atlanta	0.431	-0.24%	Atlanta	0.430	-0.48%	Houston	0.429	-6.77%
11	Chicago	0.432	Chicago	0.421	-2.44%	Chicago	0.411	-4.88%	Chicago	0.400	-7.32%
12	Washington	0.418	Washington	0.405	-3.03%	Washington	0.392	-6.07%	Phoenix	0.387	-1.26%
13	Philadelphia	0.413	Philadelphia	0.401	-2.99%	Philadelphia	0.389	-5.98%	Washington	0.380	-9.10%
14	Phoenix	0.392	Phoenix	0.390	-0.42%	Phoenix	0.388	-0.84%	Philadelphia	0.376	-8.97%
15	Boston	0.381	Jersey City	0.372	-0.35%	Jersey City	0.370	-0.69%	Jersey City	0.369	-1.04%
16	Salt Lake City	0.379	Boston	0.370	-2.92%	Sacramento	0.363	-0.74%	Sacramento	0.362	-1.11%
17	Boston	0.373	Salt Lake City	0.367	-3.19%	Boston	0.359	-5.83%	Boston	0.351	-5.99%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
19	Jersey City	0.373	Boston	0.366	-2.00%	Boston	0.358	-4.00%	San Jose	0.349	-1.54%
20	Buffalo	0.368	Sacramento	0.364	-0.37%	Salt Lake City	0.355	-6.38%	Boston	0.348	-8.75%
21	Sacramento	0.366	Buffalo	0.356	-3.42%	San Jose	0.351	-1.03%	Salt Lake City	0.343	-9.58%
23	Minneapolis	0.358	San Jose	0.353	-0.51%	St. Louis	0.347	-2.72%	St. Louis	0.342	-4.08%
24	St. Louis	0.357	St. Louis	0.352	-1.36%	Minneapolis	0.343	-4.06%	Minneapolis	0.336	-6.09%
25	San Jose	0.354	Minneapolis	0.350	-2.03%	Buffalo	0.343	-6.85%	Buffalo	0.331	-10.27%
26	Denver	0.325	Denver	0.319	-1.89%	Denver	0.313	-3.78%	Denver	0.306	-5.67%
27	Baltimore	0.318	Baltimore	0.303	-4.61%	Charlotte	0.292	-3.76%	Charlotte	0.286	-5.64%
28	Charlotte	0.303	Charlotte	0.298	-1.88%	Baltimore	0.288	-9.23%	Baltimore	0.274	-13.84%
29	Dallas	0.300	Dallas	0.291	-3.21%	Dallas	0.281	-6.43%	Dallas	0.271	-9.64%
30	Miami	0.297	Miami	0.287	-3.22%	Miami	0.278	-6.45%	New York	0.269	-5.69%
31	Baltimore	0.296	Baltimore	0.284	-3.79%	New York	0.274	-3.79%	Miami	0.268	-9.67%
32	New York	0.285	New York	0.280	-1.90%	Baltimore	0.273	-7.58%	Baltimore	0.262	-11.36%
33	Cleveland	0.265	Cleveland	0.252	-4.80%	Cleveland	0.239	-9.60%	Cleveland	0.227	-14.40%
34	Pittsburgh	0.256	Pittsburgh	0.244	-4.38%	Pittsburgh	0.233	-8.76%	Pittsburgh	0.222	-13.14%
35	Cleveland	0.229	Cleveland	0.219	-4.03%	Cleveland	0.210	-8.07%	Cleveland	0.201	-12.10%

Table 6-93 Economic Sensitivity Test for Method 2

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.702	New York	0.713	1.50%	New York	0.723	3.01%	New York	0.734	4.51%
2	Oakland	0.513	Oakland	0.521	1.64%	Oakland	0.530	3.28%	Oakland	0.538	4.92%
3	Los Angeles	0.512	Los Angeles	0.518	1.04%	Los Angeles	0.523	2.08%	Los Angeles	0.528	3.12%
4	San Diego	0.493	San Diego	0.499	1.21%	San Diego	0.505	2.43%	San Diego	0.511	3.64%
5	San Francisco	0.484	San Francisco	0.478	-1.39%	Houston	0.478	4.02%	Houston	0.488	6.03%
6	Los Angeles	0.468	Houston	0.469	2.01%	San Francisco	0.471	-2.79%	Portland	0.472	0.92%
7	Portland	0.467	Portland	0.469	0.31%	Portland	0.470	0.62%	Atlanta	0.470	8.68%
8	Houston	0.460	Los Angeles	0.468	0.00%	Los Angeles	0.468	0.00%	Los Angeles	0.468	0.00%
9	Seattle	0.448	Atlanta	0.445	2.89%	Atlanta	0.457	5.79%	Chicago	0.466	7.88%
10	Atlanta	0.432	Chicago	0.443	2.63%	Chicago	0.454	5.25%	San Francisco	0.464	-4.18%
11	Chicago	0.432	Seattle	0.440	-1.60%	Washington	0.446	6.71%	Washington	0.460	10.07%
12	Washington	0.418	Washington	0.432	3.36%	Philadelphia	0.440	6.56%	Philadelphia	0.454	9.84%
13	Philadelphia	0.413	Philadelphia	0.427	3.28%	Seattle	0.433	-3.20%	Seattle	0.426	-4.79%
14	Phoenix	0.392	Phoenix	0.397	1.45%	Boston	0.404	6.07%	Boston	0.416	9.11%
15	Boston	0.381	Boston	0.393	3.04%	Phoenix	0.403	2.90%	Phoenix	0.409	4.34%
16	Salt Lake City	0.379	Salt Lake City	0.389	2.42%	Salt Lake City	0.398	4.85%	Salt Lake City	0.407	7.27%
17	Boston	0.373	Boston	0.379	1.62%	Boston	0.385	3.24%	Boston	0.391	4.85%

	Base Case		0.3			0.35			0.4		
Rank	**City**	**CSI**	**City**	**CSI**	**% change**	**City**	**CSI**	**% change**	**City**	**CSI**	**% change**
19	Jersey City	0.373	Jersey City	0.376	0.86%	Jersey City	0.379	1.72%	Sacramento	0.385	5.35%
20	Buffalo	0.368	Sacramento	0.372	1.78%	Sacramento	0.379	3.56%	Jersey City	0.383	2.57%
21	Sacramento	0.366	Buffalo	0.371	0.65%	St. Louis	0.374	4.75%	St. Louis	0.382	7.13%
23	Minneapolis	0.358	Minneapolis	0.365	2.07%	Buffalo	0.373	1.29%	Minneapolis	0.380	6.22%
24	St. Louis	0.357	St. Louis	0.365	2.38%	Minneapolis	0.373	4.14%	Buffalo	0.376	1.94%
25	San Jose	0.354	San Jose	0.353	-0.35%	San Jose	0.352	-0.70%	San Jose	0.351	-1.05%
26	Denver	0.325	Denver	0.332	2.11%	Denver	0.339	4.21%	Baltimore	0.348	9.40%
27	Baltimore	0.318	Baltimore	0.328	3.13%	Baltimore	0.338	6.27%	Denver	0.345	6.32%
28	Charlotte	0.303	Charlotte	0.307	1.25%	Miami	0.315	5.94%	Miami	0.323	8.92%
29	Dallas	0.300	Miami	0.306	2.97%	Charlotte	0.311	2.50%	Charlotte	0.315	3.74%
30	Miami	0.297	Dallas	0.303	0.91%	Baltimore	0.306	3.63%	Baltimore	0.312	5.44%
31	Baltimore	0.296	Baltimore	0.301	1.81%	Dallas	0.306	1.82%	Dallas	0.308	2.73%
32	New York	0.285	New York	0.292	2.40%	New York	0.299	4.80%	New York	0.306	7.21%
33	Cleveland	0.265	Cleveland	0.269	1.67%	Cleveland	0.274	3.34%	Cleveland	0.278	5.00%
34	Pittsburgh	0.256	Pittsburgh	0.258	0.86%	Pittsburgh	0.260	1.72%	Pittsburgh	0.262	2.59%
35	Cleveland	0.229	Cleveland	0.235	2.71%	Cleveland	0.241	5.42%	Cleveland	0.247	8.13%

Table 6-94 Social Sensitivity Test for Method 2

	Base Case		0.3			0.35			0.4		
Rank	**City**	**CSI**	**City**	**CSI**	**% change**	**City**	**CSI**	**% change**	**City**	**CSI**	**% change**
1	New York	0.702	New York	0.696	-0.85%	New York	0.690	-1.70%	New York	0.684	-2.54%
2	Oakland	0.513	Los Angeles	0.515	0.59%	San Francisco	0.543	12.01%	San Francisco	0.572	18.02%
3	Los Angeles	0.512	San Francisco	0.514	6.01%	Los Angeles	0.518	1.18%	Los Angeles	0.521	1.77%
4	San Diego	0.493	Oakland	0.506	-1.36%	Oakland	0.499	-2.72%	Houston	0.518	12.55%
5	San Francisco	0.484	San Diego	0.492	-0.14%	Houston	0.498	8.37%	Oakland	0.492	-4.08%
6	Los Angeles	0.468	Houston	0.479	4.18%	San Diego	0.492	-0.27%	San Diego	0.491	-0.41%
7	Portland	0.467	Los Angeles	0.473	1.02%	Portland	0.478	2.20%	Portland	0.483	3.30%
8	Houston	0.460	Portland	0.473	1.10%	Los Angeles	0.477	2.03%	Los Angeles	0.482	3.05%
9	Seattle	0.448	Seattle	0.450	0.47%	Seattle	0.452	0.95%	Seattle	0.454	1.42%
10	Atlanta	0.432	Atlanta	0.438	1.39%	Atlanta	0.444	2.77%	Atlanta	0.450	4.16%
11	Chicago	0.432	Chicago	0.435	0.74%	Chicago	0.438	1.48%	Chicago	0.441	2.23%
12	Washington	0.418	Washington	0.423	1.22%	Washington	0.428	2.45%	Washington	0.433	3.67%
13	Philadelphia	0.413	Philadelphia	0.416	0.76%	Philadelphia	0.420	1.53%	Buffalo	0.428	16.18%
14	Phoenix	0.392	Phoenix	0.399	1.79%	Buffalo	0.408	10.79%	Philadelphia	0.423	2.29%
15	Boston	0.381	Boston	0.394	3.24%	Boston	0.406	6.48%	Boston	0.418	9.72%
16	Salt Lake City	0.379	Salt Lake City	0.391	3.15%	Phoenix	0.406	3.59%	Salt Lake City	0.415	9.44%
17	Boston	0.373	Buffalo	0.388	5.39%	Salt Lake City	0.403	6.29%	Phoenix	0.413	5.38%
19	Jersey City	0.373	Boston	0.384	2.91%	Boston	0.395	5.82%	Boston	0.406	8.73%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
20	Buffalo	0.368	Jersey City	0.376	0.68%	San Jose	0.385	8.63%	San Jose	0.400	12.95%
21	Sacramento	0.366	Sacramento	0.375	2.58%	Sacramento	0.384	5.15%	Sacramento	0.394	7.73%
23	Minneapolis	0.358	San Jose	0.370	4.32%	Minneapolis	0.380	6.11%	Minneapolis	0.390	9.16%
24	St. Louis	0.357	Minneapolis	0.369	3.05%	Jersey City	0.378	1.36%	Jersey City	0.381	2.03%
25	San Jose	0.354	St. Louis	0.363	1.75%	St. Louis	0.369	3.50%	St. Louis	0.375	5.25%
26	Denver	0.325	Denver	0.335	3.26%	Baltimore	0.353	10.98%	Baltimore	0.370	16.46%
27	Baltimore	0.318	Baltimore	0.335	5.49%	Denver	0.346	6.51%	Denver	0.357	9.77%
28	Charlotte	0.303	Charlotte	0.316	4.30%	Charlotte	0.329	8.61%	Charlotte	0.343	12.91%
29	Dallas	0.300	Dallas	0.314	4.57%	Dallas	0.328	9.14%	Baltimore	0.342	15.74%
30	Miami	0.297	Baltimore	0.311	5.25%	Baltimore	0.327	10.49%	Dallas	0.341	13.71%
31	Baltimore	0.296	Miami	0.307	3.51%	Miami	0.318	7.01%	Miami	0.328	10.52%
32	New York	0.285	New York	0.291	1.95%	New York	0.296	3.90%	Pittsburgh	0.303	18.54%
33	Cleveland	0.265	Cleveland	0.272	2.92%	Pittsburgh	0.287	12.36%	New York	0.302	5.85%
34	Pittsburgh	0.256	Pittsburgh	0.271	6.18%	Cleveland	0.280	5.83%	Cleveland	0.288	8.75%
35	Cleveland	0.229	Cleveland	0.232	1.55%	Cleveland	0.236	3.11%	Cleveland	0.239	4.66%

Table 6-95 System Effectiveness Sensitivity for Method 2

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.702	New York	0.706	0.53%	New York	0.709	1.06%	New York	0.713	1.58%
2	Oakland	0.513	Los Angeles	0.512	-0.07%	Los Angeles	0.512	-0.14%	Los Angeles	0.511	-0.22%
3	Los Angeles	0.512	Oakland	0.498	-3.00%	Oakland	0.482	-6.00%	Oakland	0.467	-9.00%
4	San Diego	0.493	San Diego	0.473	-4.01%	San Francisco	0.457	-5.72%	Los Angeles	0.446	-4.76%
5	San Francisco	0.484	San Francisco	0.471	-2.86%	San Diego	0.453	-8.01%	San Francisco	0.443	-8.58%
6	Los Angeles	0.468	Los Angeles	0.461	-1.59%	Los Angeles	0.453	-3.17%	San Diego	0.434	-12.02%
7	Portland	0.467	Portland	0.455	-2.64%	Portland	0.443	-5.27%	Portland	0.430	-7.91%
8	Houston	0.460	Houston	0.442	-3.94%	Houston	0.424	-7.87%	Chicago	0.420	-2.79%
9	Seattle	0.448	Chicago	0.428	-0.93%	Chicago	0.424	-1.86%	Houston	0.406	-11.81%
10	Atlanta	0.432	Seattle	0.427	-4.62%	Seattle	0.406	-9.25%	Philadelphia	0.400	-3.17%
11	Chicago	0.432	Atlanta	0.415	-4.04%	Washington	0.405	-3.09%	Washington	0.398	-4.64%
12	Washington	0.418	Washington	0.411	-1.55%	Philadelphia	0.405	-2.11%	Seattle	0.386	-13.87%
13	Philadelphia	0.413	Philadelphia	0.409	-1.06%	Atlanta	0.397	-8.09%	Atlanta	0.380	-12.13%
14	Phoenix	0.392	Phoenix	0.381	-2.82%	Phoenix	0.370	-5.64%	Jersey City	0.360	-3.57%
15	Boston	0.381	Salt Lake City	0.370	-2.38%	Jersey City	0.364	-2.38%	Phoenix	0.359	-8.46%
16	Salt Lake City	0.379	Jersey City	0.369	-1.19%	Salt Lake City	0.361	-4.76%	Salt Lake City	0.352	-7.14%
17	Boston	0.373	Boston	0.368	-3.36%	Boston	0.356	-6.72%	Boston	0.345	-7.59%
19	Jersey City	0.373	Boston	0.364	-2.53%	Boston	0.354	-5.06%	Boston	0.343	-10.09%
20	Buffalo	0.368	Buffalo	0.359	-2.62%	Buffalo	0.349	-5.23%	Buffalo	0.339	-7.85%
21	Sacramento	0.366	Sacramento	0.351	-3.99%	St. Louis	0.337	-5.53%	St. Louis	0.327	-8.29%
23	Minneapolis	0.358	St. Louis	0.347	-2.76%	Sacramento	0.336	-7.98%	Minneapolis	0.325	-9.28%
24	St. Louis	0.357	Minneapolis	0.347	-3.09%	Minneapolis	0.336	-6.19%	Sacramento	0.322	-11.97%
25	San Jose	0.354	San Jose	0.342	-3.45%	San Jose	0.330	-6.91%	San Jose	0.318	-10.36%
26	Denver	0.325	Denver	0.314	-3.47%	Denver	0.302	-6.94%	Denver	0.291	-10.42%
27	Baltimore	0.318	Baltimore	0.305	-4.01%	Baltimore	0.292	-8.01%	Dallas	0.280	-6.79%

	Base Case		0.3			0.35			0.4		
Rank	**City**	**CSI**	**City**	**CSI**	**% change**	**City**	**CSI**	**% change**	**City**	**CSI**	**% change**
28	Charlotte	0.303	Dallas	0.293	-2.26%	Dallas	0.287	-4.53%	Baltimore	0.280	-12.02%
29	Dallas	0.300	Charlotte	0.292	-3.67%	Charlotte	0.281	-7.34%	Charlotte	0.270	-11.01%
30	Miami	0.297	Miami	0.287	-3.25%	Miami	0.278	-6.51%	Miami	0.268	-9.76%
31	Baltimore	0.296	Baltimore	0.286	-3.27%	Baltimore	0.276	-6.55%	Baltimore	0.267	-9.82%
32	New York	0.285	New York	0.278	-2.46%	New York	0.271	-4.91%	Cleveland	0.266	0.65%
33	Cleveland	0.265	Cleveland	0.265	0.22%	Cleveland	0.266	0.43%	New York	0.264	-7.37%
34	Pittsburgh	0.256	Pittsburgh	0.249	-2.66%	Pittsburgh	0.242	-5.32%	Pittsburgh	0.235	-7.99%
35	Cleveland	0.229	Cleveland	0.228	-0.23%	Cleveland	0.227	-0.46%	Cleveland	0.227	-0.70%

Table 6-96 Environmental Sensitivity for Method 3

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.787	New York	0.801	1.73%	New York	0.801	1.73%	New York	0.814	3.45%
2	Los Angeles	0.643	Los Angeles	0.660	2.72%	Los Angeles	0.660	2.72%	Los Angeles	0.678	5.44%
3	Los Angeles	0.643	Los Angeles	0.660	2.72%	Los Angeles	0.660	2.72%	Los Angeles	0.678	5.44%
4	Oakland	0.607	Oakland	0.633	4.38%	Oakland	0.633	4.38%	Oakland	0.660	8.75%
5	Chicago	0.589	Chicago	0.607	3.04%	Chicago	0.607	3.04%	San Diego	0.632	9.99%
6	Portland	0.578	Portland	0.604	4.66%	Portland	0.604	4.66%	Portland	0.631	9.33%
7	San Diego	0.575	San Diego	0.603	4.99%	San Diego	0.603	4.99%	Chicago	0.625	6.07%
8	San Francisco	0.554	San Francisco	0.576	4.04%	San Francisco	0.576	4.04%	Atlanta	0.601	9.65%
9	Atlanta	0.548	Atlanta	0.574	4.83%	Atlanta	0.574	4.83%	San Francisco	0.599	8.08%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
10	Houston	0.545	Houston	0.568	4.23%	Houston	0.568	4.23%	Houston	0.591	8.46%
11	Philadelphia	0.543	Jersey City	0.563	4.91%	Jersey City	0.563	4.91%	Jersey City	0.589	9.83%
12	Jersey City	0.536	Philadelphia	0.558	2.94%	Philadelphia	0.558	2.94%	Philadelphia	0.574	5.87%
13	Washington	0.530	Boston	0.539	3.62%	Boston	0.539	3.62%	Seattle	0.565	13.69%
14	Boston	0.521	Boston	0.539	3.62%	Boston	0.539	3.62%	Boston	0.558	7.24%
15	Boston	0.521	Phoenix	0.537	5.69%	Phoenix	0.537	5.69%	Boston	0.558	7.24%
16	Phoenix	0.508	Washington	0.537	1.21%	Washington	0.537	1.21%	Sacramento	0.558	9.94%
17	Sacramento	0.507	Sacramento	0.532	4.97%	Sacramento	0.532	4.97%	St. Louis	0.546	9.33%
19	Salt Lake City	0.507	Seattle	0.531	6.84%	Seattle	0.531	6.84%	Washington	0.543	2.42%
20	St. Louis	0.499	St. Louis	0.523	4.67%	St. Louis	0.523	4.67%	Minneapolis	0.542	8.80%
21	Minneapolis	0.498	Salt Lake City	0.521	2.86%	Salt Lake City	0.521	2.86%	Salt Lake City	0.536	5.73%
23	Seattle	0.497	Minneapolis	0.520	4.40%	Minneapolis	0.520	4.40%	San Jose	0.514	12.15%
24	Buffalo	0.467	Denver	0.489	4.90%	Denver	0.489	4.90%	Denver	0.512	9.80%
25	Denver	0.466	San Jose	0.486	6.08%	San Jose	0.486	6.08%	Buffalo	0.505	8.16%
26	San Jose	0.458	Buffalo	0.486	4.08%	Buffalo	0.486	4.08%	Charlotte	0.498	10.22%
27	Charlotte	0.452	Charlotte	0.475	5.11%	Charlotte	0.475	5.11%	Miami	0.468	7.34%
28	Miami	0.436	Miami	0.452	3.67%	Miami	0.452	3.67%	New York SI	0.458	13.09%
29	New York SI	0.405	New York SI	0.432	6.54%	New York SI	0.432	6.54%	Dallas	0.439	9.08%
30	Dallas	0.403	Dallas	0.421	4.54%	Dallas	0.421	4.54%	Baltimore	0.329	-0.24%
31	Baltimore	0.330	Baltimore	0.330	-0.12%	Baltimore	0.330	-0.12%	Baltimore	0.329	-0.24%
32	Baltimore	0.330	Baltimore	0.330	-0.12%	Baltimore	0.330	-0.12%	Pittsburgh	0.266	-0.95%
33	Pittsburgh	0.269	Pittsburgh	0.268	-0.47%	Pittsburgh	0.268	-0.47%	Cleveland	0.196	-14.29%
34	Cleveland	0.228	Cleveland	0.212	-7.14%	Cleveland	0.212	-7.14%	Cleveland	0.196	-14.29%
35	Cleveland	0.228	Cleveland	0.212	-7.14%	Cleveland	0.212	-7.14%	Phoenix	0.566	11.38%

Table 6-97 Economic Sensitivity for Method 3

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.512	New York	0.522	1.96%	New York	0.522	1.96%	New York	0.532	3.92%
2	Los Angeles	0.784	Los Angeles	0.795	1.37%	Los Angeles	0.795	1.37%	Los Angeles	0.806	2.74%
3	Los Angeles	0.509	Los Angeles	0.509	-0.10%	Los Angeles	0.509	-0.10%	Los Angeles	0.508	-0.20%
4	Oakland	0.383	Chicago	0.388	1.26%	Chicago	0.388	1.26%	Chicago	0.393	2.52%
5	Chicago	0.538	Oakland	0.548	2.03%	Oakland	0.548	2.03%	Oakland	0.559	4.06%
6	San Diego	0.537	San Diego	0.550	2.40%	San Diego	0.550	2.40%	Washington	0.563	4.80%
7	Portland	0.343	Portland	0.355	3.49%	Portland	0.355	3.49%	San Diego	0.367	6.98%
8	Philadelphia	0.531	Washington	0.540	1.73%	Washington	0.540	1.73%	Philadelphia	0.549	3.45%
9	Washington	0.426	Philadelphia	0.433	1.44%	Philadelphia	0.433	1.44%	Portland	0.439	2.87%
10	Atlanta	0.253	Atlanta	0.262	3.56%	Atlanta	0.262	3.56%	Atlanta	0.271	7.12%
11	Houston	0.577	Houston	0.582	0.95%	Houston	0.582	0.95%	Houston	0.588	1.90%
12	San Francisco	0.581	Boston	0.582	0.16%	Boston	0.582	0.16%	Boston	0.583	0.31%
13	Boston	0.626	Boston	0.628	0.18%	Boston	0.628	0.18%	Boston	0.629	0.37%
14	Boston	0.550	San Francisco	0.550	-0.06%	San Francisco	0.550	-0.06%	Salt Lake City	0.550	-0.13%
15	Jersey City	0.458	Jersey City	0.453	-1.08%	Jersey City	0.453	-1.08%	Jersey City	0.448	-2.16%
16	Salt Lake City	0.512	Salt Lake City	0.522	1.96%	Salt Lake City	0.522	1.96%	San Francisco	0.532	3.92%
17	Sacramento	0.443	Sacramento	0.439	-0.96%	Sacramento	0.439	-0.96%	Sacramento	0.435	-1.93%
19	Minneapolis	0.269	Minneapolis	0.268	-0.36%	Minneapolis	0.268	-0.36%	Minneapolis	0.267	-0.72%
20	St. Louis	0.343	St. Louis	0.355	3.49%	St. Louis	0.355	3.49%	St. Louis	0.367	6.98%
21	Phoenix	0.428	Phoenix	0.427	-0.19%	Phoenix	0.427	-0.19%	Phoenix	0.426	-0.38%
23	Seattle	0.253	Seattle	0.262	3.56%	Seattle	0.262	3.56%	Denver	0.271	7.12%
24	Denver	0.480	Denver	0.484	0.75%	Denver	0.484	0.75%	Seattle	0.487	1.50%
25	Buffalo	0.529	Buffalo	0.537	1.36%	Buffalo	0.537	1.36%	Miami	0.544	2.71%
26	Charlotte	0.382	Miami	0.380	-0.59%	Miami	0.380	-0.59%	Buffalo	0.378	-1.18%
27	Miami	0.480	Charlotte	0.483	0.77%	Charlotte	0.483	0.77%	Charlotte	0.487	1.53%
28	San Jose	0.498	San Jose	0.504	1.21%	San Jose	0.504	1.21%	San Jose	0.510	2.42%
29	New York SI	0.446	New York SI	0.448	0.57%	New York SI	0.448	0.57%	New York SI	0.451	1.13%
30	Dallas	0.425	Dallas	0.420	-1.21%	Dallas	0.420	-1.21%	Dallas	0.415	-2.43%
31	Baltimore	0.522	Baltimore	0.512	-1.88%	Baltimore	0.512	-1.88%	Baltimore	0.502	-3.75%
32	Baltimore	0.486	Baltimore	0.490	0.87%	Baltimore	0.490	0.87%	Baltimore	0.495	1.74%

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
33	Pittsburgh	0.551	Pittsburgh	0.556	0.93%	Pittsburgh	0.556	0.93%	Cleveland	0.561	1.87%
34	Cleveland	0.626	Cleveland	0.628	0.18%	Cleveland	0.628	0.18%	Cleveland	0.629	0.37%
35	Cleveland	0.476	Cleveland	0.474	-0.58%	Cleveland	0.474	-0.58%	Pittsburgh	0.471	-1.17%

Table 6-98 Social Sensitivity for Method 3

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.755	New York	0.737	-2.44%	New York	0.737	-2.44%	New York	0.718	-4.88%
2	Los Angeles	0.615	Los Angeles	0.604	-1.72%	Los Angeles	0.604	-1.72%	Los Angeles	0.594	-3.44%
3	Los Angeles	0.615	Los Angeles	0.604	-1.72%	Los Angeles	0.604	-1.72%	Los Angeles	0.594	-3.44%
4	Oakland	0.578	Oakland	0.576	-0.34%	Oakland	0.576	-0.34%	Oakland	0.574	-0.68%
5	Chicago	0.565	Chicago	0.558	-1.15%	Chicago	0.558	-1.15%	San Francisco	0.565	4.08%
6	Portland	0.547	San Francisco	0.554	2.04%	San Francisco	0.554	2.04%	Chicago	0.552	-2.30%
7	San Francisco	0.543	Portland	0.544	-0.61%	Portland	0.544	-0.61%	Portland	0.541	-1.21%
8	San Diego	0.542	San Diego	0.538	-0.73%	San Diego	0.538	-0.73%	San Diego	0.534	-1.46%
9	Washington	0.524	Washington	0.525	0.07%	Washington	0.525	0.07%	Washington	0.525	0.14%
10	Houston	0.521	Houston	0.519	-0.27%	Houston	0.519	-0.27%	Houston	0.518	-0.55%
11	Atlanta	0.516	Atlanta	0.511	-1.03%	Atlanta	0.511	-1.03%	Atlanta	0.506	-2.05%
12	Philadelphia	0.515	Philadelphia	0.504	-2.15%	Philadelphia	0.504	-2.15%	Boston	0.500	-0.20%
13	Jersey City	0.502	Boston	0.501	-0.10%	Boston	0.501	-0.10%	Salt Lake City	0.498	0.72%
14	Boston	0.501	Salt Lake City	0.496	0.36%	Salt Lake City	0.496	0.36%	Philadelphia	0.493	-4.31%
15	Salt Lake City	0.494	Jersey City	0.494	-1.58%	Jersey City	0.494	-1.58%	Jersey City	0.486	-3.17%
16	Sacramento	0.482	Sacramento	0.483	0.10%	Sacramento	0.483	0.10%	Sacramento	0.483	0.21%
17	Minneapolis	0.476	Minneapolis	0.476	-0.01%	Minneapolis	0.476	-0.01%	Minneapolis	0.476	-0.03%
19	Phoenix	0.476	Phoenix	0.472	-0.73%	Phoenix	0.472	-0.73%	Phoenix	0.469	-1.45%
20	Phoenix	0.476	Phoenix	0.472	-0.73%	Phoenix	0.472	-0.73%	Phoenix	0.469	-1.45%
21	St. Louis	0.473	St. Louis	0.470	-0.62%	St. Louis	0.470	-0.62%	Buffalo	0.467	2.92%
23	Seattle	0.463	Seattle	0.464	0.11%	Seattle	0.464	0.11%	St. Louis	0.467	-1.23%

24	Buffalo	0.454	Buffalo	0.461	1.46%	Buffalo	0.461	1.46%	Seattle	0.464	0.21%
25	Denver	0.445	Denver	0.446	0.27%	Denver	0.446	0.27%	Denver	0.447	0.54%
26	Charlotte	0.433	Charlotte	0.438	1.11%	Charlotte	0.438	1.11%	Charlotte	0.443	2.21%
27	San Jose	0.432	San Jose	0.433	0.36%	San Jose	0.433	0.36%	San Jose	0.435	0.73%
28	Miami	0.423	Miami	0.426	0.71%	Miami	0.426	0.71%	Miami	0.429	1.41%
29	Dallas	0.387	Dallas	0.390	0.70%	Dallas	0.390	0.70%	Dallas	0.392	1.40%
30	New York SI	0.368	New York SI	0.357	-2.99%	New York SI	0.357	-2.99%	Baltimore	0.360	5.80%
31	Baltimore	0.341	Baltimore	0.350	2.90%	Baltimore	0.350	2.90%	Baltimore	0.360	5.80%
32	Baltimore	0.341	Baltimore	0.350	2.90%	Baltimore	0.350	2.90%	New York SI	0.346	-5.99%
33	Pittsburgh	0.287	Pittsburgh	0.305	6.00%	Pittsburgh	0.305	6.00%	Pittsburgh	0.322	12.00%
34	Cleveland	0.255	Cleveland	0.265	3.97%	Cleveland	0.265	3.97%	Cleveland	0.275	7.94%
35	Cleveland	0.255	Cleveland	0.265	3.97%	Cleveland	0.265	3.97%	Cleveland	0.275	7.94%

Table 6-99 System Effectiveness Sensitivity for Method 3

	Base Case		0.3			0.35			0.4		
Rank	City	CSI	City	CSI	% change	City	CSI	% change	City	CSI	% change
1	New York	0.768	New York	0.762	-0.77%	New York	0.762	-0.77%	New York	0.756	-1.54%
2	Los Angeles	0.617	Los Angeles	0.609	-1.30%	Los Angeles	0.609	-1.30%	Los Angeles	0.601	-2.61%
3	Los Angeles	0.617	Los Angeles	0.609	-1.30%	Los Angeles	0.609	-1.30%	Los Angeles	0.601	-2.61%
4	Oakland	0.555	Chicago	0.537	-3.05%	Chicago	0.537	-3.05%	Chicago	0.521	-6.09%
5	Chicago	0.554	Oakland	0.529	-4.60%	Oakland	0.529	-4.60%	Oakland	0.504	-9.19%
6	Portland	0.527	Portland	0.504	-4.41%	Portland	0.504	-4.41%	Portland	0.481	-8.82%
7	San Diego	0.516	Philadelphia	0.495	-3.08%	Philadelphia	0.495	-3.08%	Philadelphia	0.479	-6.15%
8	Philadelphia	0.511	San Diego	0.486	-5.79%	San Diego	0.486	-5.79%	Washington	0.465	-7.81%
9	San Francisco	0.508	Washington	0.485	-3.91%	Washington	0.485	-3.91%	San Francisco	0.461	-9.32%
10	Washington	0.504	San Francisco	0.484	-4.66%	San Francisco	0.484	-4.66%	San Diego	0.456	-11.58%
11	Houston	0.493	Jersey City	0.474	-3.64%	Jersey City	0.474	-3.64%	Jersey City	0.456	-7.28%
12	Jersey City	0.492	Houston	0.465	-5.84%	Houston	0.465	-5.84%	Houston	0.436	-11.68%
13	Atlanta	0.491	Atlanta	0.461	-6.17%	Atlanta	0.461	-6.17%	Atlanta	0.431	-12.34%
14	Boston	0.473	Salt Lake City	0.448	-4.75%	Salt Lake City	0.448	-4.75%	Salt Lake City	0.425	-9.50%
15	Boston	0.473	Boston	0.445	-5.99%	Boston	0.445	-5.99%	Boston	0.417	-11.99%
16	Salt Lake City	0.470	Boston	0.445	-5.99%	Boston	0.445	-5.99%	Boston	0.417	-11.99%

17	Phoenix	0.457	Phoenix	0.434	-4.97%	Phoenix	0.434	-4.97%	Phoenix	0.411	-9.93%
19	Sacramento	0.452	St. Louis	0.428	-5.32%	St. Louis	0.428	-5.32%	St. Louis	0.404	-10.65%
20	St. Louis	0.452	Minneapolis	0.425	-5.64%	Minneapolis	0.425	-5.64%	Minneapolis	0.400	-11.29%
21	Minneapolis	0.451	Sacramento	0.422	-6.62%	Sacramento	0.422	-6.62%	Sacramento	0.392	-13.24%
23	Seattle	0.433	Buffalo	0.405	-5.02%	Buffalo	0.405	-5.02%	Buffalo	0.383	-10.04%
24	Buffalo	0.426	Seattle	0.404	-6.82%	Seattle	0.404	-6.82%	Seattle	0.374	-13.64%
25	Denver	0.417	Denver	0.390	-6.37%	Denver	0.390	-6.37%	Denver	0.364	-12.75%
26	San Jose	0.406	San Jose	0.382	-5.97%	San Jose	0.382	-5.97%	San Jose	0.357	-11.95%
27	Charlotte	0.402	Charlotte	0.375	-6.74%	Charlotte	0.375	-6.74%	Charlotte	0.347	-13.48%
28	Miami	0.395	Miami	0.370	-6.36%	Miami	0.370	-6.36%	Miami	0.345	-12.72%
29	Dallas	0.366	Dallas	0.347	-5.13%	Dallas	0.347	-5.13%	Dallas	0.328	-10.25%
30	New York SI	0.358	New York SI	0.338	-5.68%	New York SI	0.338	-5.68%	New York SI	0.318	-11.35%
31	Baltimore	0.309	Baltimore	0.288	-6.93%	Baltimore	0.288	-6.93%	Baltimore	0.266	-13.86%
32	Baltimore	0.309	Baltimore	0.288	-6.93%	Baltimore	0.288	-6.93%	Baltimore	0.266	-13.86%
33	Pittsburgh	0.255	Pittsburgh	0.240	-5.88%	Pittsburgh	0.240	-5.88%	Cleveland	0.236	-2.35%
34	Cleveland	0.242	Cleveland	0.239	-1.17%	Cleveland	0.239	-1.17%	Cleveland	0.236	-2.35%
35	Cleveland	0.242	Cleveland	0.239	-1.17%	Cleveland	0.239	-1.17%	Pittsburgh	0.225	-11.76%

Across all sets of tables similar results are observed. However, there are differences in ranking across all tests. For test 2, there are no changes to the overall populations of the highest tier except for in the economic test and system effectiveness test where the population changes by 1. However, the quantities of LR and HR systems in the top 5 systems did not change. This indicates that the method 2 results are much more stable than the method 1 results likely due to the lack of negative values as well as the greater range of values in the method 1 index set. For method 3 analysis, a similar stability is observed. There are four HR and one LR system in each category's top performance set under base conditions, however for environmental and social sensitivity testing it is observed that the split becomes three HR and two LR.

6.8.2 Sensitivity Summary

Across all three tests similar findings were observed with varying degrees of sensitivity:

- For environmental sensitivity testing it is found that LR systems in the highest performance tier receive beneficial results, however some HR systems do as well. Although most see a negative change. In general LR performs better in the environmental category.
- For economic sensitivity, HR systems increase in rank while some top performing LR systems decrease in rank. Overall, there are more HR systems in the top tier at the .40 weighting mark, indicating that higher economic weighting favours high performance HR systems and that high performance HR systems may perform in general better under the economic category.
- For the social sensitivity test, the ranking changes with LR systems seeing great increases, and most HR seeing small changes. This indicates overall better performance under the social category for high performing LR systems.
- For the system effectiveness sensitivity one LR system leaves the highest performance category and is replaced by a HR system under the 0.40 weighting level. Otherwise, there is little change in ranking, however most systems see a decrease in CSI under these tests. The change in ranking is due to smaller

decreases rather than gains, which shows that HR may have a slight advantage, in general, in this category, which is a similar finding to method 1.

Chapter 7: PTSMAP Application to Decision Making: Vancouver UBC Corridor

7.1 Introduction

7.1.1 Overview

This chapter provides a second demonstration of the PTSMAP framework utilizing study data from Vancouver, British Columbia. No unique data has been developed for this research and chapter. Instead data available in the study report was used to demonstrate the decision making context of the tool.

While the previous chapter focussed on the research applications of the PTSMAP framework, Chapter 7 provides an example of decision making scenario 1. In this scenario the overall PTSMAP sustainability categories are applied, however different factors have been substituted due to availability of data in the UBC study. The goal of this chapter is to demonstrate how the PTSMAP framework along with CSI methodologies can be used in a common transportation planning situation – in this case, selecting a preferred alternative for developing rapid transit along a corridor.

7.1.1 UBC/Broadway Corridor Study Selection and Scope

The PTSMAP framework is proposed as an alternative decision making tool that would complement the results of the in-depth study by presenting them in a sustainability focussed manner. While other techniques such as cost benefit analysis may be used in decision making, the PTSMAP framework offers another indication of how each project performs in developing a sustainable transportation system. In chapter 5 decision making applications of the framework were specified:

- Decision Making 1: the use of the PTSMAP methodology to compare within a set of alternatives being evaluated
- Decision Making 2: the use of the PTSMAP methodology to compare alternatives to previously developed targets or benchmarks.

The analysis contained in this chapter is based on data provided publically by TransLink in the UBC Line Rapid Transit Study Phase 2 Evaluation report -

http://www.translink.ca/~/media/Documents/plans_and_projects/rapid_transit_projects/UBC/alternatives_evaluation/UBC_Line_Rapid_Transit_Study_Phase_2_Alternatives_Evaluation.ashx - based on work conducted by consultants. As public transit planning projects are considerably complex – typically involving large teams of experts for modelling, visioning, and option development (among other tasks) – this section of the thesis is not focussed on planning new modes or the creation of planning studies. These efforts are considered out of scope of this research.

Rather, this thesis will demonstrate the ability of the PTSMAP framework to be applied in the Decision Making 1 Scenario based on the outputs provided by a planning study. This study was selected because it presented multiple public transit options for consideration, has a well-documented multiple account evaluation that is considered appropriate for adopting into a PTSMAP evaluation, and also considered multiple transit modes. This multi-modal nature of the study allows further comparison of modes in a unique context.

7.2 Study Background

7.2.1 Overview

The UBC Line study focussed on analysing the potential for rapid transit along Vancouver's Broadway corridor. The UBC Line routes included in the study run east to west in Vancouver from Commercial Drive to the University of British Columbia. While different routes were proposed for the study, the Broadway corridor, running west from Commercial Drive, was the focal route of the study. As Central Broadway is expected to continue to grow in population and employment, the area is considered an important transit destination where further rapid transit development would be beneficial (Steer Davies Gleave, 2012).

The Phase 2 report analysed in this thesis focussed on evaluating a short list of transit alternatives for the corridor based on a Multiple Account Evaluation approach. Multiple Account Evaluation techniques allow decision makers to assess the strengths and weaknesses of each option using qualitative and quantitative data. Each account represents a priority area or theme for the project and is composed of sub criteria and inputs – similar to the categorical indices and factors in the PTSMAP formulation.

While the aim of the study was to assist in the selection of an alternative to progress, as of October 2013 no option has been selected and further discussions on how to proceed in the corridor are underway.

7.2.2 Study Objectives

The study and alternative development process for the UBC Line project was oriented around a project mission with accompanying objectives. These objectives formed the basis for developing the accounts used in the multiple-account evaluation. Figure 7-1 shows the mission and objectives of the study.

Figure 7-1 Phase 2 Report: UBC Corridor Mission and Objectives

Project Mission

To plan a rapid transit service that is accessible, convenient, safe, reliable and environmentally and financially sustainable that integrates with the regional transportation system and contributes to the achievement of transportation, environmental and land use objectives and targets.

Project Objectives

- *A fast, reliable and efficient service that meets current and future capacity needs, supports achieving transportation targets and integrates with and strengthens the regional transit network and other modes;*
- *An affordable and cost-effective service;*
- *A service that contributes to meeting wider environmental sustainability targets and objectives by attracting new riders, supporting changes to land use and reducing vehicle kilometres travelled;*
- *A service that supports current and future land use development along the Corridor and at UBC and integrates with the surrounding neighbourhoods through high quality urban design;*
- *A service that encourages economic development by improving access to existing and future major regional destinations and local businesses by transit while continuing to facilitate goods movement;*
- *A safe, secure and accessible service that also improves access to rapid transit for all and brings positive benefit to the surrounding communities, including managing impacts of rapid transit;*
- *A service that is constructible and operable.*

(Steer Davies Gleave, 2012, p. 19)

7.2.3 Study Structure- Evaluation and Data

MAE frameworks use quantitative and qualitative data across a number of accounts composed of inputs/criteria. Each account represents an important goal or objective for the project or future transit system and the individual criteria or inputs are direct ways the project's impact on the account can be assessed. The study utilized direct comparison for inputs/criteria that have quantitative scores while qualitative evaluations used a 7 point scale composed of significant benefit, moderate benefit, slight benefit, neutral, slightly adverse, moderately adverse, and significantly adverse.

Seven accounts were selected and developed for the study. Each account has a number of criteria that assess an option's progress towards the given metric. A time frame was set to compare options in 2021 as well as 2041, although not all indicators were developed for both years. The accounts used in this study as well as their associated inputs/criteria, as stated in the report, are shared in Figure 7-2. As noted in the figure, there are a variety of accounts that cover a significant breadth of transportation and urban issues that are associated with the development of a new transit system.

For this thesis, only select quantitative data has been utilized in the PTSMAP framework from the various accounts to demonstrate how a study such as this could utilize the framework to interpret the results based on sustainability. The inputs that are evaluated on the benefit/adverse scale used for qualitative factors are not treated in this thesis.

Figure 7-2 UBC Line Account Description Table

Evaluation Criteria

Account	Objective	Criteria
Economic Development	A service that encourages economic development by improving access to existing and future major regional destinations and local businesses by transit while continuing to facilitate goods movement	Construction effects, tax effects and goods movement
Environment	A service that contributes to meeting wider environmental sustainability targets and objectives by attracting new riders, supporting changes to land use and reducing vehicle-kilometres travelled	Emission reductions, noise and vibration, biodiversity, water environment, parks and open space
Financial	An affordable and cost-effective service	Capital cost, operating cost, cost-effectiveness
Social and Community	A safe, secure and accessible service that also improves access to rapid transit for all and brings positive benefit to the surrounding communities, including managing impacts of rapid transit	Health effects, low income population served, safety, community cohesion, heritage and archaeology
Transportation	A fast, reliable and efficient service that meets current and future capacity needs, supports achieving transportation targets and integrates with and strengthens the regional transit network and other modes	Transit user effects, non-transit user effects, transit network/system access, reliability, capacity and expandability
Urban Development	A service that supports current and future land use development along the Corridor and at UBC and integrates with the surrounding neighbourhoods through high quality urban design	Land use integration, land use potential, property requirements, urban design potential
Deliverability	A service that is constructible and operable	Constructability, acceptability, funding and affordability

(Steer Davies Gleave, 2012, p. iii)

7.3 UBC Line Options

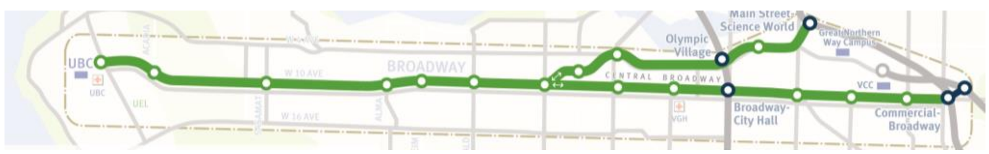
The UBC Line study considered five options for transit development along the corridor. These options are shown in Figure 7-3 as taken from the UBC Line report.

Figure 7-3 UBC Line Alternatives

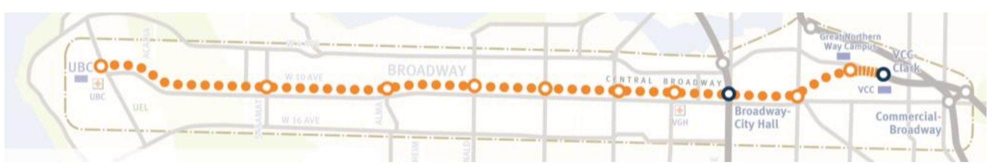
BRT - At-grade BRT route from UBC to Commercial-Broadway via University Blvd, West 10th Ave and Broadway using diesel articulated buses[1].

LRT1 - At-grade LRT route from UBC to Commercial/Broadway via University Blvd, West 10th Ave and Broadway.

LRT2 - combines LRT1 with a second branch from Broadway/Arbutus to Main Street-Science World via the CPR right-of-way, the City of Vancouver Streetcar route and Main St.



RRT - Mainly tunnelled route via University Blvd, West 10th Ave, Broadway, Great Northern Way as an extension of the existing Millennium Line SkyTrain from VCC-Clark.



Combination Alternative 1 - Combination of RRT from VCC Clark to Arbutus with the portion of the LRT2 route operating from UBC to Main Street/Science World.

Combination Alternative 2 – a combination of RRT from VCC Clark to Arbutus with the BRT alternative using diesel buses.

Best Bus - represents the best that can be achieved relying on conventional buses in the study area and demonstrates the impacts and benefits of bus service improvements within the corridor including local, semi-express (B-Line) and express bus services.

(Steer Davies Gleave, 2012, pp. V-VI)

All options were compared to a business as usual case where operations along the corridor would scale up based on historic trends into the future. For inputs/criteria that are based on changes (such as a change in emissions) the comparison is to the future year forecasted base case.

7.4 Case Study Methodology

7.4.1 Accounts, Indicators, and Data

As this study presented a comprehensive effort to plan and evaluate potential options for expanded rapid transit in the region, not all indicators used in the study are used in this thesis. Rather, a selection of indicators contained within the report have been put forward and aligned with the quadruple bottom line framework suggested by Jeon (2007) and adapted for this research in Chapters 5 & 6.

The accounts put forward by the study, and shared in Figure7-2, have been sorted into the four quadruple bottom line framework shown in Table 7-1. The following sub sections of this section outline which indicators have been selected and the rationale behind their use. Discrepancies between the indicators used in chapters4-6 are also discussed.

Table 7-1 MAE Accounts sorted into PTSMAP

Environmental	**Social**
- Environment	- Social and community - Transportation
Economic	**Effectiveness**
- Economic development - Financial - Deliverability	- Transportation - Urban Development

As shown in table 7-1, there is not a clear delineation of accounts into the quadruple bottom line framework. The individual inputs/criteria of each account are therefore sorted. These sorted criteria are shown in table 7-2. Only criteria used in the analysis are shown. Factors showing a (+) are to be maximized and factors showing a (-) are to be minimized.

Table 7-2MAE Factors Sorted into PTSMAP

Category	Factor	Indicators	Category	Factor	Indicators
Environment	GHgs	+ Change in Transit GHg	Social	Accessibility	+ Low Income Population served
		- Transit GHg from Construction			+ Access to population
	Pollutants	+Change in criteria air contaminants (NH3, NOx, PM10, PM2.5, SOx, VOC)			+ Access to employment
				Health	+ Collision Cost Savings (Millions pv)
Economic	System Costs	- Capital	System Effectiveness	System Usage	+ Trip generation
		- Operating			+ Mode share & Auto pkm reduction
	Transit Use and Economy	+ Contributions GDP			+ pkm on Transit
	User Costs	- Travel Time			

7.4.2 Environmental Indicators

Of the environmental indicators considered in the study the following are considered - greenhouse gas (GHg) emissions (construction/life cycle, and operation) as well as criteria air contaminants emissions.

GHg emissions are based on the emissions of constructing the system as well as emissions from the vehicles themselves based on the form of energy used. An analytical model was used to calculate the reduction in emissions of GHgs due to a decrease in vehicle kilometres travelled (VKT) with the addition of a new rapid transit system. Two inputs are used from the report: the change in GHg due to the new transit systems and the emissions of the system construction. For this thesis a combination of change in transit emissions and change in auto fleet is considered as one indicator representing GHg emissions for operation while a second indicator is shown to represent GHg emissions of construction.

Emissions of criteria air contaminants, which include NH_3, NO_x, PM_{10}, $PM_{2.5}$, SO_x, VOC, are also considered in the study and in this thesis. These emissions are similarly based on first modelling the change in VKT and the resulting change in emissions. In this thesis the indicator is used as presented in the report. All emission values will be weighted equally to sum and create one factor/indicator.

The following inputs are not considered as they are treated in a qualitative manner in the report:

- Noise and vibrations;
- Biodiversity;
- Water environments
- Parks and open spaces

Raw energy consumption is not provided by the report so this factor is not discussed in this analysis.

7.4.3 Economic Indicators

Economic indicators used in this thesis are capital costs, operating costs, contribution to GDP, and user costs in the form of travel time. As all systems exist in the same region it is likely that a similar user monetary cost/fare will be incurred for all developments so this factor is not considered.

Capital costs are based on the cost of constructing each system – the variances occur due to differences in technology and alignment. Different construction windows are set for each option to reflect the different needs of each system type.

Operating costs are based on a number of factors (Vehicle Operations- wages, Vehicle Operations- fuel/power, Vehicle Maintenance, Administration). Costs are based on operating assumptions from the AM peak that were annualized. Contribution to GDP was calculated using the BC Input Output Model and capital costs. Values as stated in the report were used for all three factors (capital costs, operating costs, and contribution to GDP).

Travel time as a user cost was based on a runtime model using basic transit system assumptions. The values used in this analysis are taken directly from the report.

Additional factors not used in this analysis include the following economic development inputs:

- Operating effects;
- Taxes; and
- Goods movement.

As well as the cost effectiveness finance input. In the report, the cost effectiveness input is based on a number of savings accrued due to improved transit service and is portrayed as a benefit/cost ratio for each mode. This thesis seeks to provide a complimentary measure of project sustainability through the calculation of a CSI so the benefit/cost ratios were not included as indicators.

7.4.4 Social Indicators

The social indicators considered in this analysis represent both health and accessibility. The indicators for accessibility are: low income population served in the catchment area, population in catchment area, and employment in the catchment area. While the study utilized 800m and 400m catchment areas, only the 800m catchment areas are considered in this study.

The study report used census data to generate the low income population served. Low income population was defined based on a cut-off of after-tax income where families spend at least 20 % more of their after-tax income than the average family on food, shelter and clothing. This factor is considered a measure of accessibility in line with the findings of the literature review and is consistent with the definition of sustainability utilized in this research. Access opportunities for low income families can be considered in line with notions of advancing or sustaining social progress/justice.

The second two accessibility factors, which represent population and jobs served by the area are also in line with the theory behind accessibility measurement outlined in the literature review. Both these indicators were under the transportation account in the report. While a more precise tool may be used in future work, these two indicators together demonstrate how well the transit service can directly serve individuals in the community.

Unlike the analysis of NTD systems, this analysis does contain a health metric. In this instance health benefits are measured financially through an estimate of the reduction in costs due to road accidents of the system.

The following social indicators were not included as they were measured qualitatively:

- Safety and security
- Community cohesion
- Heritage and archaeology

7.4.5 System Effectiveness Indicators

While various urban development and transportation account inputs could be used to assess system effectiveness, only trip generation, mode share, and auto pkm reductions were considered.

Trip generation outlines the system's ability to generate trips – in terms that are consistent with the definition of effectiveness used in this thesis. This indicator is derived from analytical modelling and uses number of trips as a count. Passenger kilometer travelled or pkm represents the total distance travelled on the system and is another reflection of use. In this case, the pkm difference from the base case is used as a metric. An additional lens on system effectiveness is mode split. Modesplit represents the relative attractiveness and uptake of the mode.

Finally, reduction in auto pkm should be included as it further represents the system's ability to mitigate the need for auto based travel. However, the planning window for this indicator did not match the others (2021) so it has been excluded. Mode split can be used as a stand in and it is argued that the reduction in auto vkt is represented in the environmental indicators – however the impact of improved transit on the broader transport networks effectiveness is correlated to reduced VKT, but due to the nature of this indicator it is not measured in this research.

7.4.6 Analysis Methodology

This case study uses CSI technique 3 (re-scaling) on all the indicators mentioned above. Recalling equation 5-6, individual indicator scores may be normalized with the following equation:

$$n_i = \frac{x_i - \min(all\ x)}{\max(all\ x) - \min(all\ x)}$$

Where min values are the least performing options and max values are the greatest performing options. The procedure for decision making scenario 1 is followed for the analysis of all inputs. First, the values are normalized within categories and then categorical indices are calculated. Finally, a CSI value is derived.

Weighting values are set to equal values within indicators and for summing category indices – similar to the approach used in chapter 6. With weightings and normalized values, a CSI can be calculated using equation 5-2.

$$CSI_q = w_e \sum_{i=1}^{j} w_i E_{i,q} + w_s \sum_{i=1}^{j} w_i S_{i,q} + w_n \sum_{i=1}^{j} w_i N_{i,q} + w_y \sum_{i=1}^{j} w_i Y_{i,q}$$

7.5 **Sustainability Calculations**

This section provides an overview of the input data, normalized data, and categorical indices for each category. It concludes by sharing the CSI values for each alternative in the study.

7.5.1 Environmental Factors

Table 7-3 displays the environmental inputs used in this study.

Table 7-3 Environmental Inputs

	Environment								
	Change in GHgs (kilotons)		Change in Pollutants (tons)						
	Change in net transit GHg emission during operation	Transit GHg from Construction	**CO**	**NH3**	**NOx**	**PM10**	**PM2.5**	**SOx**	**VO**
BRT	-5	19	-7,378	-50	-452	-15	-15	-8	-8
LRT1	-137	78	-9,485	-89	-1,302	-70	-70	-61	-61
LRT2	-136	109	-9,362	-88	-1,295	-70	-70	-61	-61
RRT	-132	211	-21,805	-171	-2,015	-93	-93	-72	-72
Combo 1	-137	162	-17,731	-144	-1,780	-85	-85	-68	-68
Combo 2	4	110	-18,489	-125	-1,095	-36	-36	-17	-17

These inputs have been normalized using the re-scaling equation. The outputs of this normalization process are shown in Table 7-4.

Table 7-4 Re-scaled Environmental Factors

	Environment								
	GHgs		Pollutants						
	Change in Transit GHg	Transit GHg from Construction	**CO**	**NH3**	**NOx**	**PM10**	**PM2.5**	**SOx**	**VO**
BRT	0.064	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LRT1	1.000	0.693	0.146	0.322	0.544	0.705	0.705	0.828	0.828
LRT2	0.993	0.531	0.138	0.314	0.539	0.705	0.705	0.828	0.828
RRT	0.965	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Combo 1	1.000	0.255	0.718	0.777	0.850	0.897	0.897	0.938	0.938
Combo 2	0.000	0.526	0.770	0.620	0.411	0.269	0.269	0.141	0.141

The composite category indices for the environment are shown in Table 7-5.

Table 7-5 Environmental Category index

	Environmental Index
Combo 1	0.743
RRT	0.741
LRT1	0.715
LRT2	0.671
Combo 2	0.319
BRT	0.266

As noted in Table7-5, combo 1 attains the highest environmental performance, however RRT is very close (0.27% difference).

7.5.2 Economic Factors

Table 7-6 displays the economic inputs included in this study.

Table 7-6 Economic Inputs

	Economic			
	System Costs		Economic Development	User Costs
	Capital	Operating	Contributions GDP	Travel Time
BRT	409	14	171	30.4
LRT1	1,112	11.9	480	33.4
LRT2	1,332	15.7	614	28.1
RRT	3,010	12.9	1632	28.1
Combo 1	2,666	14	1247	18.5
Combo 2	1,966	19.6	987	29.3

Table 7-7 display the normalized economic factors base on re-scaling.

Table 7-7 Re-scaled Economic Factors

	Economic			
	System Costs		Economic Development	User Costs\
	Capital (million $)	Operating (million $)	Contributions GDP (million $)	Travel Time (minutes)
BRT	1.000	0.727	0.000	0.201
LRT1	0.730	1.000	0.211	0.000
LRT2	0.645	0.506	0.303	0.356
RRT	0.000	0.870	1.000	0.356
Combo 1	0.132	0.727	0.736	1.000
Combo 2	0.401	0.000	0.559	0.275

Finally, table 7-8 displays the composite indices for the economic category.

Table 7-8 Economic Category Index

	Economic Index
Combo 1	0.649
RRT	0.556
LRT1	0.485
BRT	0.482
LRT2	0.453
Combo 2	0.309

As shown in the table, combo 1 provides the highest performance. Unlike the environmental factors, there is less direct competition under the economic category.

7.5.3 Social Factors

Table 7-9 outlines the social inputs used in this case study.

Table 7-9 Social Inputs

	Social			
	Accessibility			Health
	Low Income Population (thousands)	Population (thousands)	Jobs (thousands)	Collision Cost Savings (Millions $)
BRT	16.5	47	49	27
LRT1	16.5	47	49	33
LRT2	19	59	68	31
RRT	14.6	38	49	77
Combo 1	17.4	55	69	60
Combo 2	17.1	51	55	63

The values have been rescaled in table 7-10.

Table 7-10 Rescaled Social Factors

	Social			
	Accessibility			Health
	Low Income Population	Population	Jobs	Collision Cost Savings (Millions pv)
BRT	0.432	0.429	0.000	0.000
LRT1	0.432	0.429	0.000	0.120
LRT2	1.000	1.000	0.950	0.080
RRT	0.000	0.000	0.000	1.000
Combo 1	0.636	0.810	1.000	0.660
Combo 2	0.568	0.619	0.300	0.720

Finally, the category indices for the social category are shown in table 7-11.

Table 7-11 Social Category Index

	Social Index
Combo 1	0.738
Combo 2	0.608
LRT2	0.532
RRT	0.500
LRT1	0.203
BRT	0.143

Again, combination 1 provides the highest performance. Unlike previous options, combination 2 provides a high level of performance.

7.5.4 System Effectiveness Factors

Table 7-12 shows the system effectiveness inputs and table 7-13 shows their rescaled forms. Finally, Table 7-14 shows the composite index for the systems effectiveness category.

Table 7-12 System Effectiveness Inputs

	System Effectiveness		
	System usage		
	Trip generation (million trips)	Corridor Mode share	PKm
BRT	88	27.60%	16840
LRT1	123	27.60%	21280
LRT2	129	27.70%	22272
RRT	254	29.80%	79198
Combo 1	258	29.30%	63564
Combo 2	251	29.20%	56603

Table 7-13 Re-scaled System Effectiveness Factors

	System Effectiveness		
	System usage		
	Trip generation	Mode share	PKm
BRT	0.341	0.926	0.213
LRT1	0.477	0.926	0.269
LRT2	0.500	0.930	0.281
RRT	0.984	1.000	1.000
Combo 1	1.000	0.983	0.803
Combo 2	0.973	0.980	0.715

Table 7-14 System Effectiveness Index

	System Effectiveness Index
RRT	0.995
Combo 1	0.929
Combo 2	0.889
LRT2	0.570
LRT1	0.557
BRT	0.493

Based on the system effectiveness analysis, RRT is shown to provide the greatest performance.

7.5.5 UBC Line CSI

With all category indices calculated, the CSI values for each system can be determined. As with the past examples, each category index receives the same weighting. The CSI values for each mode are shown in table 7-15.

Table 7-15 UBC Line CSI Values

	CSI
Combo 1	0.76465739
RRT	0.69810636
LRT2	0.55635245
Combo 2	0.53112909
LRT1	0.4901048
BRT	0.34620165

From this analysis it is shown that Combo 1 provides the highest CSI value. Throughout all category assessments combo 1 always achieved high performance, which is reflected in this assessment. Combo 1 combines LRT and RRT options in order to provide a blend of rapid transit alternatives in one complete line – which is noticeable in the ranking. This option has similar benefits to the RRT but also is lower cost due to its LRT component. Due to the combination of the system, it even exceeds RRT in performance.

From this assessment there are two major takeaways:

- The option with the highest CSI performance doesn't need to have the highest scores in each category. Composite indicators require strong performance across a number of options, but may perform lower in others – such as the lower performance on capital costs of the Combo 1 or RRT values.
- While all options were specifically designed for the corridor, the combination 1 option attains highest performance. This could be associated with the unique blend of services used to create this option. This highlights ideas in the literature review as well as findings in the NTD case study – sustainability performance and high transit performance can be traced back to context specific solutions.

7.6 Conclusion

This chapter highlights how to apply the PTSMAP framework to a study that was not developed with PTSMAP in mind. Due to the MAE nature of the study there were few issues adapting the basic data to the PTSMAP framework. However, it is important to note that this case study is limited.

First, a number of indicators were not used in the PTSMAP case study. Currently the PTSMAP framework can use qualitative data for contextualizing the CSI scores, but does not have an explicit methodology to treat qualitative assessment. Further research is required into how to better incorporate these aspects of research and planning studies.

Secondly, some factors with quantitative values were not included – either to avoid double counting or due to incompatibility with timing. Refining the framework in future research to have improved flexibility may increase its uptake and utilization.

An important point from this case study is that the PTSMAP framework also has further room to expand and better represent sustainable transportation. The consideration of broader urban issues and land development impacts, which were not included in the PTSMAP framework, presents an important idea that is in line with the literature reviewed in this thesis. This study included urban development goals as part of transit analysis – while these goals would have been difficult to measure with the PTSMAP framework used with the NTD set, further analysis and development of transit and urban development could lead to a standardized set of indicators similar to the environmental or economic issues currently considered in the PTSMAP framework. Urban development and changes in land use are inextricably linked to transit – their exclusion in the chapter 5&6 framework may limit the potential applicability of this research in further contexts or in decision making. Further development is required.

However, the framework was designed to manage specifically mobility issues and transit. Future research should seek to resolve this. Two path ways that immediately exist could be by adding urban indicators more extensively into the four bottom lines or adding a fifth category that explicitly collects these factors. The former, is in line with the sustainability approach espoused in this research – to break down sustainability concepts into buckets or sectors of analysis and use appropriate indicators to track progress. Urban issues could fit into these categories as well – and under such a framework, urban issues would be seen under an environmental, social, economic, or effectiveness lens, rather than as being a distinct issue as part of sustainability.

Chapter 8: Sustainable Transportation Conceptual Case study: Calgary, Alberta, Canada

8.1 Introduction

8.1.1 Overview

This thesis includes case studies to explore the conceptual, theoretical, and analytical dimensions of sustainable transportation using real world examples. By drawing upon case study specific literature, including research papers and municipal plans and documents, as well as concepts outlined in Chapters 2 and 3 this case study analyzes transportation and sustainability for the City of Calgary in Canada. Calgary has been selected as a case study because it provides an excellent opportunity to engage with challenges associated with unsustainable auto oriented transportation and policies that attempt to grapple with these challenges.

Specifically, this case study uses high level transportation data to outline trends in travel behavior in the city in order to frame the challenge of unsustainable auto oriented travel. This challenge is highlighted as it is one of great relevance in the 21st century with energy intensive transport related to many global issues. Auto dependant development is also of relevance in many cities around the world and is cautioned against within many rapidly developing cities in urbanizing countries for which this research is applicable as a decision support tool. Furthermore, many of the concepts illustrated in the literature review sections, such as push and pull factors for sustainable transport policy, auto dependence, and social/economic/environment issues in sustainability, were ideal for exploring within the Calgary context.

This study was conducted with limited engagement with official institutions, such as the municipal government, and thus only data available in public reports, plans, and presentations was available. Inasmuch, this study was conducted as a high level analysis of the city's transport system – as operational and high resolution data were unavailable, they have not been used. This was a significant limitation of the study; therefore, the study is focused on different measures for improvement and suggests ways to continue the analysis and dive deeper into the issues as more data becomes available.

8.1.2 Chapter Organization

In section 2, an overview of the city is provided to help the reader understand the context of the city. In section 3 the city's transportation system is explored and outlined. In section 4 the case study's problem is explicitly framed as auto oriented travel and its associated sprawl based urban growth. The need to explore alternatives from a half century growth cycle of car oriented transportation and sprawl oriented land use in order to develop a more sustainable city that mitigates the various economic, social, and environmental impacts that come along with sprawl and auto dependence are also framed. Section 5 outlines theoretical plans for how to approach this problem through transit oriented measures for short, middle, and long term systemic development. Section6 outlines specific improvements that will facilitate this plan. Finally, section 7 provides a summary of the case study and recommendations for further research and next steps.

8.2 Overview of Calgary

8.2.1 Context

The City of Calgary is the major population centre in the southern half of the Province of Alberta in Canada. As Canada's fourth largest city by population, Calgary is a rapidly expanding economic hub. Geographically, the city is over 704 square kilometres in area and is divided into four quadrants: NW, SW, NE, and SE (Statistics Canada, 2012). The broader area surrounding The City is composed of communities and suburbs that together form the Calgary Metropolitan Area (CMA), which is the fourth most populous metropolitan area in the nation, after Toronto, Montreal, Vancouver, and Ottawa.

*8.2.2 **Geographic and Demographic data***

As of the 2011 census the population of The City was 1,090,936, while the CMA was home to 1,365,200 inhabitants (Statistics Canada, 2006). These figures highlight the City's role as the key population centre of the CMA. The City's annual growth of population in 2010 was 1.81%, which is in line with growth trends from the previous decade (Statistics Canada, 2006). Of this growth about half is due to natural increase, while the remaining half is due to migration from other parts of the province and the country. The CMA saw a growth of 2.2% in 2010 (Calgary Economic Development, 2009). The City of Calgary and surrounding population centres are low density settlements with the city having a density of 1,360.2 people per km^2 (Statistics Canada, 2006). Continued growth will be driven by migration and natural growth, similar to growth observed in the city and CMA over the past 10 years. By 2020 it is expected the CMA will be home to 1,519,400 inhabitants, while the city will hold 1,244,800 inhabitants (Calgary Economic Development, 2009). By 2030 the city is expected to be almost 1.6 million people and host to over 900,000 jobs. By 2030 seniors will make up a larger portion of the population than youth, which may have serious ramifications of economic activity. The City has a progressive parks and recreation policy which has provided the city's population with many parks and green space. The total area covered by green space in Calgary is over 80 square kilometres, which accounts for over 12% of the city's footprint (City of Calgary, 2009b).

8.2.3 Economic Overview

As of 2006, 770,000 people were employed across a variety of sectors in the City of Calgary (Statistics Canada, 2011). Calgary is home to a diverse economy with contributions from a variety of sectors with Oil and Gas, Construction, Finances, Professional Services, and Manufacturing being the major sectors. Employment is also dispersed throughout diverse areas, with professional services (such as health care, engineering, finances), manufacturing, and construction being large employers. Despite high employment and economic growth, over 12.5% of Calgarians lived below the low income poverty line (income of $19,261/inhabitant) as of 2003. Poverty can be viewed as a radicalized issue in Calgary, with new comers and first nation/aboriginal populations over represented in the below poverty line income bracket (City of Calgary, 2009a).

8.3 Transportation System Challenges and Opportunities in Calgary

8.3.1 System Overview

The City of Calgary features an expansive network of roadways, pathways, and transit ways that facilitate multimodal transportation. The City saw most of its urban growth in the automobile era, and as a result, the transportation system that has been developed has an automobile bias. While there is provision for active modes and transit, there is still a heavy auto focus within the trip making behaviour of Calgarians. As noted in the literature review, auto trips and auto networks tend towards unsustainable transport and unsustainable travel.

8.3.2 Auto Network

The transportation system contains a large network of roads that fit into a hierarchal set of road types that include freeways, arterial, collector, and local roads. A "Skeletal Network" of major east-west and north-south freeways and arterials has been developed to facilitate automobile flow around the city effectively (City of Calgary, 2002). While all the roadways in this network provide access to downtown, none directly pass through it in an effort to encourage localized activity and local trips. In 2011, less than half of all commute trips destined to downtown were conducted using automobiles (33% were auto trips), however 77% of all daily trips across the city are auto trips (City of Calgary, 2009d) (City of Calgary, 2012).

8.3.3 Transit Network

The City of Calgary runs a public transportation service known as "Calgary Transit". Calgary Transit has provided transit services for over 100 years in the region, with its original inception being an electric street car company. Over the years Calgary Transit evolved as an integral component of the city's transportation network and currently provides a wide variety of services for Calgarians including LRT, traditional bus, light BRT, and para-transit. In 2011 there were 96,215,000 trips taken by Calgary Transit passengers (City of Calgary, 2009d).

As of January 2012, the bus system is composed of 161 routes that provide a variety of travel choices for Calgarians including circular routes, feeder routes (to BRT or LRT), local routes, and arterial/corridor travel options. The BRT network has 5 routes, including access to the airport, that provide larger buses for typically longer routes. Currently, these BRT routes are lacking many characteristics of many of the highest performance BRT systems around the world – especially with regards to separated right of ways and off bus ticketing. However, they do provide frequent service on high capacity buses that integrate ITS technologies. According to the RouteAhead, Calgary's long term transit plan there are currently plans to greatly expand the BRT network with a variety of BRT services. These projects include southwest and north cross town in street BRT routes with signal priorities (Calgary Transit, 2013). Additional BRT projects using 'transitways', which direct transit on either transit only lanes on an existing road, a right of way separated from traffic or shoulders on an existing roadway , either separately or in combination, are also in the planning stages (Calgary Transit, 2013).

The 2011 BRT Network Plan also outlines current considerations to expand BRT service and provide North-South mobility to South Western communities not served by LRT through transit only or busway style service (Calgary Transit, 2011).

An LRT network of 48.8 km and two routes (South to North West, North East to Downtown) is also provided (City of Calgary, 2009d). The two routes share a transit corridor with BRT and bus service along 7th ave in the downtown core. The LRT system is called the "C-Train" and it has average of 252,600 weekday boardings, (APTA, 2011).

8.3.4 Active Mode Network

The city has developed an extensive pathway system for active modes that provides over 635 km of paved surface for cyclists and pedestrians. An additional 290km of on street bikeways are provided. These bikeways are integrated, where possible, to the pathway system (City of Calgary, 2009d).

8.4 Mobility Challenges – Analysis of Unsustainable Transport

8.4.1 Problem Framing – Sprawl and Automobile Dependence

The City of Calgary's transportation system does a decent job providing high reliability and high level of service transportation for most citizens. According to Statistics Canada, Calgary has the second lowest average commute time, at 26 minutes, out of all major cities in Canada (Turcotte, 2010). In global quality of living scales, such as the Economist Intelligence Unit annual liveability analysis, Calgary also typically fares well in the transportation category. From a travel time perspective, this frames the system very positively; however, when the lens is expanded to look at a whole suite of systemic factors, including environmental, social, and economic issues, there are many "under the surface challenges" that need to be explored and addressed to enable long term sustainable growth in the Calgary region. Low travel time is facilitated by a focus on auto oriented development for most trips – as a result the road network has been over developed contributing to auto dominance and sprawl. The essential challenge in hand is the current sprawl-auto dependent development pattern that the city is locked in. The following sections will explore indicators for this problem and some of the impacts in order to frame the challenges at hand. While chapter 4 will outline potential measures that can form a set of solutions.

These challenges have also been identified in Plan-it Calgary, a community visioning process and strategy (City of Calgary, 2009b). As part of the costs and benefits of different potential development patterns for Calgary, Plan-it Calgary discusses two potential growth scenarios – one scenario continues to see Calgary grow in a dispersed manner characterized by heavy auto use and sprawled suburbs – a business as usual approach (BAU approach).The second focused on a recommended direction that focuses on density and transit oriented development as guiding principles (recommended approach) (City of Calgary, 2009c). Given the previously discussed increases in population, continued road development to fuel the above mode split as a means of mobility will be an expensive prospect – both in terms of development and implementation costs, but also in terms of lost potential for a more sustainable urban form. In essence, the auto oriented mode split provides an important warning signal for unsustainable mobility and land development.

8.4.2 Mode Split – an early warning for unsustainable transport

In order to better understand the present and future challenges of Calgary's transportation system mode share can be used as an initial indicator. While it is not a precise indicator for any particular transportation challenge, it is a strong starting point as it can reflect energy usage, the amount of infrastructure required to provide transport, and key socioeconomic trends in trip making behaviour. Inasmuch, the City has selected mode split as an important indicator for land use and mobility planning – used for both evaluation and goal setting (City of Calgary, 2011). Table 8-1 outlines the daily average mode share of Calgary's transportation system as of 2009.

Table 8-1: Average Daily Mode Split for Calgary 2009

Mode of Transportation	**Per cent of all daily trips**
Walk/Cycle	14
Transit	9
Vehicles (SOV & HOV)	77

Adapted from: Calgary Transportation Plan (City of Calgary, 2009d)

As noted in the table, when analyzing all travel, the automobile mode dominates transportation in the City. As mentioned in the system outline, the City of Calgary has grown and evolved in the automobile era. The high auto mode share reflects this trend in urban development. Intensive infrastructure spending in roadways, particularly large multilane freeways, within the municipal area has facilitated rapid mobility for automobile users that live in the suburbs. However, these same roadways have also contributed to negative transportation land use interactions and a high degree of sprawl, with a few major activity centres, such as the downtown core and the University of Calgary and its 2 teaching hospitals amongst large sprawling residential areas. The problems associated with sprawl are well known – in the long term these auto oriented development patterns hinder sustainable growth.

8.4.3 Further Analysis of Auto Dependence

As a centre of employment, transportation within and into the downtown core has been closely studied in order to understand how Calgarians access employment and commute to work. In order to better understand the model split in Calgary, downtown trip behaviour can be analysed using available data.

Table 8-2 outlines the breakdown of trips to downtown Calgary for the am peak, on average, in 2010.

Table 8-2: Average Travel to Downtown Mode Split Calgary in 2010

Mode of Transportation	**Per cent of all daily trips**
Walk/Cycle	11
Transit	50
Auto - driver	33
Auto- passenger	6

Adapted from: Calgary Transportation Plan (City of Calgary, 2009d)

For commuter trips in the AM peak to downtown, the majority of trips use transit, rather than private auto. The majority of these trips are based on the bus, BRT, and LRT networks that funnel travellers downtown. A brief analysis of the difference between overall trips and trips to downtown presents the possibility that the system works well to move commuters into downtown on transit, but for non-commute trips and trips to other locations, the capacity provided by non-auto modes is either being underutilized or is not yet been developed.

For school trips, commute trips destined to industrial parts of the city, or to other lower density employment centres automobiles are still the dominant mode. This adds nuance to the auto dependence problem as identified by the overall mode split – currently Calgarians are using transit to travel to downtown, yet for other trips there is a focus on automobile.

8.4.4 Environmental, Social, and Economic Impacts of Car Dependence

The problem of auto dependence as identified by auto dominated mode spit can cause a series of sustainability related challenges for the city. These challenges are outlined in Table 8-3 based on arguments made in the literature.

Table 8-3: Unsustainable Auto-Dependence

Environmental	**Social**	**Economic**
Emissions and energy usage: automobiles require far more energy and create much greater emissions per traveller km than other modes. (Schiller, Bruun, & Kenworthy, 2010)	Community severance: intensive highway development severs communities from one another (Schiller, Bruun, & Kenworthy, 2010)	Operating cost: Plan-It scenarios predict a 14% per year higher operating costs for auto dependent growth in Calgary compared to dense growth (City of Calgary, 2009c).
Land consumption: land requirements for road and parking are greater than for other modes (Schiller, Bruun, & Kenworthy, 2010)	Community deterioration: with sprawl, communities can become bedroom communities with little interaction or sense of community (Newman & Kenworthy, 1999)	Infrastructure development cost: automobile infrastructure typically costs more to provide similar capacity to transit or active modes. (Schiller, Bruun, & Kenworthy, 2010)
Impacts on urban form: unsustainable and auto dependent transport systems will encourage urban sprawl which uses up valuable land and promotes continued auto use (Newman & Kenworthy, 1999)		

Exact data for the difference in emissions, land consumption, and social impacts are not available at this time due to the difficult nature of quantification – these challenges are identified from the literature to explore potential issues and direct future research. If it is assumed that the basic understanding of auto dependence and sprawl problems, as developed in the literature review, is held to represent reality, an increase in auto oriented development will increase emissions and land consumption, damage social fabric, and contribute to sprawl. The economic considerations are better developed and model output based data is available. Based on projections, a BAU case of auto intensive development would require 3300 km of new lanes and roads, while a denser form would require only 1100 km. If an average price of $ 5 million per/km is assumed, a stark contrast in capital costs for transportation can be drawn, with denser urban form being cheaper to develop and maintain (City of Calgary, 2009c).

8.4.5 Mode Split Explored – TDM and Transit Development

An analysis of the policy behind the limited role of auto for moving travellers downtown can provide insights into how mode shift solutions may be developed throughout the wider transportation network. The downtown mode shift provides an ideal example of travel behaviour for the city; however, it is unlikely that the city will ever see a net mode share smaller than 50% for auto (projections for the future lower the share to 60%) (City of Calgary, 2009d). Even so, key principles for shifting travel mode can be drawn and explored for broader implementation in the city. Both push and pull factors that have encouraged a gradual move away from automobile for downtown travel are noted in policy and evaluation documentation. The following factors are considered highly effective.

Push factors include:

- Limited parking: from 1996-2006 the parking stall availability in Calgary has decreased from 46.7 stalls per 100 employees to35.5 stalls per 100 employees. Current policy has put a moratorium on increasing parking in the downtown core. This has led to increased parking prices and limited ability for employees to drive to work. (City of Calgary, 2010)

- Limited Road Development: there are currently no plans to increase auto capacity within the downtown core. Arterial development around downtown has continued, which has allowed larger volumes of traffic to reach or circumvent downtown; however, there is no stated plan to add additional capacity at entrance points or through roads. (City of Calgary, 2002)

Pull factors include:

- Effective use of park and rides: C-train and BRT stations have been given free and large park and ride lots with the intention to make transit lines more accessible for travellers. While this doesn't eliminate automobile travel and its challenges (emissions, heavy land use for roads and parking) it limits the need for road expansion in the city and makes transit more accessible (Hubbel, 2006).
- Public Transit Priority: transit has been given priority at major intersections, queue jump lanes on freeways, and ITS tools (such as advanced traveller information and transit signal priority) in order to make it more attractive and encourage mode transition (City of Calgary, 2009d).

The above factors can be considered in terms of capacity reduction and displacement, as well as use of new technologies and policies to facilitate transition to other modes for a geographic area. However, in the broader Calgary context little reduction has been seen.

8.4.6 Future Options for Calgary

The connection between increased sprawl and auto dependence is a complex relationship with no one cause or solution. As the sprawl-car dependence associated with the Calgary BAU growth scenario creates long environmental, social, and economic challenges that undermine the sustainability of a city further analysis is required. Given the challenges it presents to sustainable mobility and urbanism it is important to consider measures to reduce its impact and eventually halt its spread. The policies identified in this sub chapter are interesting considerations for how to trigger mode shift. Chapter 4 builds on these principles to suggest measures to limit sprawl and diversify mode share.

8.5 Transit Improvements through TDM and Policy

8.5.1 Plan Overview and Selection

As outlined in the previous chapter, the long term sustainability mobility of Calgary is challenged by a dependence on automobile travel and increasing urban sprawl. This chapter outlines a set of measures – both policy and technical – that can be implemented to help promote sustainable transit policy. These suggestions are presented to be consistent with the results of the literature review as well as the composite sustainability analysis.

Mode split was used as a key point of analysis for sustainable transport in section 7.3 – it has also been discussed in chapter 3 as a metric for sustainable mobility. Inasmuch, this chapter's measures focus on increasing the uptake of transit for non-commuter trips as a means to contribute to halting the sprawl-car dependence loop. The measures selected have been described in literature and their selection is based upon their description in chapter 3. The proposed measures are focused on using policy and technical improvements that act as push and pull factors to attract more travellers to use transit. By building on existing policy and systemic factors that enable transit usage, while enacting push factors that will challenge more travellers to use transit, these measures will gradually increase transit mode share. The key factors to improve are transit service delivery over the short, middle, and longer term, as well as accompanying TDM measures to be discussed in chapter 5. The target for Plan-it Calgary over the long term is to achieve a total 17.5% mode share for transit. All proposed measures will be with regards to this goal (City of Calgary, 2009c).

The overall framework for tackling the auto-dependence and sprawl problem is based on the following principles:

- First, transit improvements will begin to shift more travellers to transit. This will take cars off the road and increase awareness for transit. Transport demand management concepts should be included to support the transition of travellers to transit on high potential routes.
- In the middle term, more transit routes are made viable due to systemic improvements. Further rider shift is achieved through reductions in travel time, increases in reliability, and improved trip planning at the house hold level. This reduces cars on the road and begins to chip away at the large auto mode share. New developments should be planned close to existing rapid transit systems and heavily used bus systems to provide transit oriented development.
- Finally, in the long term, larger systemic improvements, including new LRT and BRT legs, are created. These legs impact urban development and encourage transit oriented development to occur.

Specific measures that fit into this generalized approach are included in Table 8-4:

Table 8-4: Selected Problem Solving Measures

Transit Improvements	**Time Frame**
- Increased capacity of bus systems to route travellers to rapid transit options - Continue to emphasize transit supportive Transport Demand Management	- Short
- Increased use of ITS and planning tools to incentivize transit use - Emphasize Transit Oriented Development	- Middle
- Expansion of LRT and BRT network that is integrated with Transit Oriented Development Opportunities	- Long

This plan was selected as it has a direct indicator to measure (proportion of trips taken by transit) which allows for analysis and understanding of impacts. It was also selected as it enables city and transport planners to build on existing strong points, including the high downtown mode share, in order to shift travellers from cars to transit. Furthermore, it uses ideas prototyped in the downtown context that have worked, which speaks to the validity of attempting these ideas in a different manner within the Calgary context. Finally, this plan was also considered as it combines push and pull factors along with standard transit system improvements to encourage a gradual change in transit ridership. As this plan tackles sustainability from multiple perspectives, it is believed to be more effective.

8.6 Exploration of Potential Measures

Both the policy and transit improvements will now be analysed based on their potential to mitigate the problem of sprawl and auto dependence. The transit improvements have been developed in such a way that they can be scaled up over time, allowing gradual and self-reinforcing improvements to the mode split to occur. These measures are not analysed in considerable depth due to the nature of this case study and limited availability of data. This exercise is to explore the theoretical potential of these measures, which will need to be researched more thoroughly using up to date models, and data internal to the city and Calgary Transit. The costs of the following options are first generalized and then the specifics of each option are explored.

Table 8-5: Transit Improvements and Costs

Transit Improvements	Potential Source of Costs
- Increased capacity of traditional bus systems to route travellers to rapid transit options	- Implementation and rerouting of service - Additional rolling stock - Additional staffing
- Increased use of ITS and planning tools to incentivize transit use	- Development of institutional capacity for ITS/TDM work - Running and maintaining online services
- Expansion of LRT and BRT network	- Construction, planning, and operation costs

8.6.1 Transit Improvements: short term

The first proposed improvement is to stimulate increased transit ridership by providing more services that connect communities outside of walking distance from mass transit (either BRT or LRT) to these services. This increase in capacity should be characterized by improved headways, route allocation, and reliability. Transit level of service is a complex factor to determine, however there are some fundamental determinants it relies upon including reliable headways and service frequency (Dowling, 2009) . This measure suggests improvements for these two factors as well as changes to service delivery with a focus on utilizing available road space for traditional bus service where it is, on average, quicker than using the bus route to feed into a mass transit option. When the combined trip time of the mass transit option is quicker the bus route should become a feeder. Overall route structure should be based on land use/activity centres present and planned, as well as current/historic travel behaviour.

In essence, this measure seeks to minimize travel time through route selection based on current trip potential. As this is a service adjustment, it could be piloted with select communities or corridors in order to understand how to effectively run route adjustment in the Calgary context before being implemented more broadly. The efficacy of this program can be assessed based on ridership changes and travel surveys that indicate changes in personal travel time. These initial data present a system wide (ridership) and individual (travel time) perspective. While this will not immediately reduce sprawl, it has the potential to contribute to decreased auto usage which is a first step to the problem.

Trip planning as part of a suite of transport demand management (TDM) activities, at either a workplace or residential level has seen promising results in the UK (City of Calgary, 2009b). Trip planning involves working with passengers individually or in groups to develop new travel behaviours using a variety of tools and approaches. This may be applicable in the Calgary context to encourage a shift to transit.

8.6.2 Transit Improvements: middle term

A plan to improve public transport should also include a middle-term planning, ITS and marketing/TDM program that aims to complement improvements to service delivery with increased demand. This program should be focused on helping travellers make more informed choices for route selection, while improving high demand routes with regards to reliability and travel time. Integrating pull factors, such as reliable traveller information, improvements to travel time via signal priority and queue jump lanes for routes on busy corridors, and trip planning tools are a few options that have been tested in other cities with positive results (Cairns, et al., 2008). Trip planning tools, such as online tools or household travel consultations, are an effective way to encourage individuals to move from the auto mode.

Table 8-6: Middle Term Transit Measures

Measure	Metric for Effectiveness
Signal Priority and Queue Jump Lanes for Busy Routes	- Decrease in route travel time, increase in reliability for circle routes - Increase in ridership
Traveller Information, trip planning	- Utilization of tool - Changes in ridership

It is recommended that these measures be piloted in specific circumstances in order to better understand the benefits that can be derived. For example, implementing trip planning or counselling in an under capacity corridor could help transition some automobile users to transit. For signal priority and queue jump lanes, implementation should be based on feasibility (cost, geographic factors, traffic characteristics) and benefits (potential in saved travel time). These factors should be piloted and scaled up where possible in the middle term.

In order to finance these measures it is recommended that they be distributed throughout the appropriate business units within the city. For example, Transportation Planning, who handles network expansion and modification, could handle bus queue jump lanes, while the Calgary Traffic Centre would handle the analysis of where to include signal priority. Trip planning could be an expansion of typical Calgary Transit services that expands on already existing online trip planning platforms. City policy should be set so to include these costs within the day to day expenditures of already existing business units.

8.6.3 Transit Improvements: long term

Finally, in the long term, major systemic improvements in infrastructure could be explored. First, BRT routes can be provided on high potential corridors that either have high auto usage but underutilized transit potential and also on future LRT routes. The city has recently delivered a third LRT leg (Downtown to West), with two more legs (SE through downtown and North through Downtown) undergoing various stages of planning (City of Calgary, 2009d). Using BRT where possible in the middle-long term to provide mass transit and later upgrading to LRT is a strategy that mirrors the express bus to LRT mode progression used in the 70s and 80s during the initial round of LRT development (Hubbel, 2006). This approach develops familiarity with the route and created a greater induced demand effect. BRT would first be focussed on because it is a lower cost alternative to LRT and can be implemented in the shorter term while requiring less space. While the capacity may be lower than LRT, similar to the express bus approach in the 70s, it can be used to increase demand and raise interest in transit.

LRT is seen as the ultimate mode choice for the city's heavy transit corridors based on demand estimations that do not exceed 40,000 pphd – the barrier between heavy rail/metro and LRT (Thilakaratne R. S., 2011). LRT is also a less invasive system to develop than metro with typical lower costs. Given that large network expansions of over 60km are recommended by the plan-it framework, LRT is seen as an ideal choice. It can cover longer distances that are in line with Calgary's large footprint at a considerably smaller price. Financing these projects is a great concern due to their associated costs.

Developing the 60 km of additional rail could cost several billion dollars alone due to land acquisition, construction, and planning costs. Sources of funding include provincial and federal money for municipal improvements, as well as municipal funding for transit system upgrades (City of Calgary, 2009c). Other potential funding could come from exploring P3s, or public private partnerships. Such a model was recently explored for funding ring-road development in Calgary between the government of Alberta and a consortium of private sector partners. As transit system is expensive and an ever present need, a wide variety of funding options should be considered. P3 measures for transit projects have started in Canada, with the first major project being the P3 to design, build, partially finance, and operate the Canada Line rail transit system that serves the Metro Vancouver region (Vancouver International Airport, Richmond, and Vancouver) in British Columbia (inTransitBC, 2012). A second example of the P3 model's use in transit development is the Confederation Line in Ottawa, a 12.5 km Light Rail Transit system that is being procured through a design, build, finance, and maintain structure (City of Ottawa, 2012).

Further analytical work, including market research and modelling, is required to understand the complete benefits for the case of the City of Calgary. As this case study is conducted to explore sustainability concepts, such work is seen as outside of the scope of this research.

8.7 Next Steps and Conclusion

8.7.1 Next Steps

The above outlined transit measures require further research and planning to be fully outlined. In order to continue the development an international best practice review of similar measures in other cities Calgary's size is recommended. This best practice review should outline other potential costs, benefits, and pathways to implementation that were not included in this basic analysis. A follow up step would include analytical modelling for system improvements along with stakeholder engagement to begin to understand the broader implications of systemic change. Institutional analysis for short and medium term measures to better understand which business units can shoulder costs and how service improvements can be implemented in a cost effective measure should also be completed.

Overall, it is believed that these measures can provide an opportunity to encourage less auto use in the short term and shape urban growth in the long term to begin to break the cycle of sprawl. These measures contribute to improved transit service delivery and access under the assumption that improvements to the background network will allow a similar mode shift to occur for all trips that occurred for downtown trips. Again, it is important to note that complementary land use policies are essential, including ones that reduce parking, foster transit oriented development, and penalize auto movement when possible.

As these measures are a start for improvement on the selected problem, further measures are included in the literature review. These additional measures are intended to complement these transit oriented measures. The problems of car dependence and sprawl are difficult to mitigate and will take concerted and well organized measures that span push and pull factors. Improving the sustainability of Calgary's transportation system is no small feat, but it is believed that well thought out transit measures can play an important role to reduce the negative impacts of heavy car ownership while the city's structures that give rise to car dependence are improved upon.

8.7.2 Conclusion

This Chapter provided an overview of the economic and geographic context of the City of Calgary as well as its current transportation network. As a growing Canadian city with a history of auto dependent development coupled with effective transit policies, Calgary is an interesting case study to contribute to the growing dialogue on sustainable transportation planning. This paper specifically has positioned Calgary's development within the context of sustainable transportation and auto dependence and has commented on the policies utilized by the city to induce demand for transit use through the use of push-pull, TDM, and sustainable transportation terminology. A temporal framework for building on the foundations laid by present policy is presented in order to maximize transit usage and reduce auto dependence.

Chapter 9: Conclusion and Recommendations

9.1 Summary

This thesis developed a multi criteria decision making framework that is applicable for sustainability analysis of existing transit systems as well as in decision making for future system development. The PTSMAP framework is a flexible tool that represents current theory and approaches in transport planning and sustainability science. This framework is characterized by its ability to be used in four scenarios depending on the analyst or researcher's needs – two scenarios for monitoring and evaluation and two for comparing or developing alternatives.

Monitoring and evaluation of existing transit systems, such as the systems analyzed in this research, is conducted in this framework based on a holistic sustainability framework. This research analyzed 33 systems -13 Heavy Rail and 20 Light Rail systems in the USA – which demonstrates the applicability of the tool for understanding system performance in a nuanced and holistic way. This analysis identifies strengths, weaknesses, and opportunities for improvement which are identified based on their annual performance and existing system configurations. All data expansion and treatment calculations were included in the analysis in order to demonstrate how sustainable mobility analysis can be conducted.

For each factor, performance was compared using performance quartiles. These performance quartiles were also used for category indices and ultimately composite sustainability indices. To further aid in data interpretation, performance categories have been established. Both the quartiles and the performance categories can enable researchers and decision makers to quickly contextualize or understand a system's performance in sustainability terms.

Sensitivity testing was also used for the analysis of the 33 scenarios in order to demonstrate the influence of expert opinion or policy scenarios on sustainability. This process expanded the reach of the findings and showed how different weightings can influence scoring.

The framework was also tested for decision support purposes using data from the TransLink UBC Line Phase 2 report. The methodology that underpins this research can be adapted to work with a number of inputs, as shown in Chapter 7. This chapter demonstrates the versatility of the tool – showing how a set of different inputs can be fitted to the PTSMAP framework to develop measures of sustainability.

In both contexts the composite indicator has been calculated in a methodology consistent with past research by prominent sustainability studies as well as general methods in transport planning and engineering . These approaches are informed by common techniques in composite indicator development and decision making. This approach has room for continued refinement and it is hoped that future research will build on it by integrating advanced concepts and tools that will create a higher precision sustainability analysis. Additionally, sustainability is an ever evolving field so over time the framework will need to be adapted to include new theories and ideas.

This thesis also presents a review of sustainable development, sustainable transport, and decision making for sustainable transportation. These three reviews are synthesized and adapted to create an approach to assessing the degree to which mass public transit systems contribute to sustainable transportation in urban areas. As a thesis, the body of work presented is intended to be useful as a primer on sustainability concepts, a demonstration of sustainability analysis, as well as a useful analysis of 33 heavy and light rail transit systems in the United States that can be built on by consultants and researchers around the world.

9.2 **Key Contributions**

This thesis sought to synthesize past research in order to develop a new framework for the analysis of public transit systems. The research also intended to apply this framework to explore the sustainability performance of different modes of rapid transit. Finally, the research was also intended to generate decision making case studies to aid in future research and planning endeavors.

The key contributions of this thesis are:

1) **Framework Development:** a new framework for analysing public transit sustainability based on the indicator approaches of past studies
2) **Modal Sustainability Analysis:** an in-depth analysis of 33 mass transit systems in the USA that comments on the modal debate. In the past, there has been a general sense of trying to establish modal superiority, however this research demonstrates rather conclusively that both LRT and HR systems can achieve high performance per passenger km across multiple sustainability areas, as well as high performance in other areas not measured per passenger km.
3) **Decision Support Demonstration: a** demonstration of how the framework can be used to inform decision making by using data and framing from the TransLink UBC Line Phase 2 report. This demonstration shows how indicator selection and CSI methodologies can provide another indicator for decision makers when considering transit projects.

9.2.1 Framework Development

The framework that was developed for this research draws on a wealth of literature and past studies in order to be consistent with these works, but also provide a new approach to analysis. This approach is comprehensive and combines many factors for transit planning that may traditionally be looked at in isolation into one overarching framework.

While the framework has roots in work by Jeon (2007), Jeon et al (2009), Haghshenas & Vaziri (2012), and Kennedy (2002) it offers a unique approach based on the selection of indicators solely for transit analysis. The framework successfully synthesizes diverse sustainability research into the quadruple-bottom line framework proposed and demonstrated by Jeon (2007) and Jeon et al (2009) to offer a new way to assess public transit.

While the foundations of this framework are based on these works, the framework itself offers a novel way to assess public transit. While past studies have proposed indicators and approaches, this study assembles these different ideas, methodologies, and sustainability theories into one comprehensive and inclusive framework that can be used in both research and decision making contexts. Additionally, the inclusion of system effectiveness as a major pillar of sustainability echoes the idea pioneered by Jeon (2007) but also shows how transit can be assessed based on the traditional triple bottom line categories with the addition of effectiveness.

The framework's key strengths are its versatility and adaptability – which allows it to contribute to future research and planning projects. The framework presents a method to analyze how systems are performing or how future systems may perform. This can allow decision makers to analyze their existing system and identify gaps in performance, and then test future scenarios to see which ones improve the system's sustainability. For example, an analysis may show a system is strong in economic indicators, such as cost effectiveness for operators but weak in social issues, such as user accessibility.

The PTSMAP framework can clearly identify such strengths and weaknesses. Future plans can be designed to improve on these weaknesses and then the plans can be tested among themselves to see which one offers the best benefit. It may be that some changes intended to resolve the challenges with low performance social indicators could cause economic or environmental losses, while others may improve the system holistically. This framework complements multiple account evaluations by adding a stronger quantitative measure, and also complements cost benefit analyses by offering an expanded measure of system performance.

In terms of adaptability, the framework can be used in many contexts due to its ability to leverage expert opinion for weightings – either in planning or research. This also enables a variety of scenarios to be tested, as shown with the sensitivity testing. Furthermore, usability was built into the tool. It can easily be used with simple excel models, which allows it to be used by planners, engineers, and decision makers working in a variety of contexts.

9.2.2 Modal Sustainability Analysis

Previous studies in transit system analysis typically considered only a few factors. Sustainability may be described in terms of social, economic, or environmental terms, but the norm in most studies is to look at a single variable – such as energy consumption. This research implements a holistic framework to understand transit system performance based on mode (HR or LR) and offers observations on how these modes perform.

By analyzing 33 systems, this thesis contributes to a new understanding of how a variety of systems as single entities perform on sustainability terms, but also shares how they perform relative to each other. These findings contribute to the modal debate in transit planning and also can provide benchmarks or aspirational values for system planning and expansion.

The complexity of analysis is underscored through three different techniques, which all share slightly different results. The thesis shows how the type of normalization used can impact the transit sustainability score.

9.2.3 Decision Support Demonstration

Finally, this research also demonstrated how this framework could be used in a real world decision making scenario. The application of the PTSMAP framework to the TransLink UBC corridor study outlines how existing data can be readily used through the framework to provide a new perspective on transit decision making. This approach is complementary to cost benefit ratios or other traditional analytic techniques and allows decision makers to now assess transit options quantitatively based on their contribution to sustainability.

9.3 **Key Findings**

This framework's application to 33 systems from the USA provides new insights into the relative performance of HR and LR systems. Past studies have only looked at single or few variables and indicators, this study applied a framework containing 4 sustainability categories and 14 indicators to offer a new perspective on comparative performance. As cities around the world strive for sustainable development, this framework and these results can be a helpful aid in future research and planning exercises.

While further research is still required, this study represents a major and new effort to compare a breadth of transit systems using an in depth sustainability lens. From this research the following general results were observed:

- For environmental performance, light rail systems attain generally better performance
- For economic performance, heavy rail systems attain generally better performance
- For social performance, light rail systems generally attain better performance
- For system effectiveness, heavy rail systems generally attain better performance

These findings were reinforced by sensitivity testing that showed as weightings increased so did the general level of performance for the modes noted above.

However, the most important finding of this research is that across all performance tiers, there are systems from both sets for all factors and indices. This demonstrates the overarching conclusion of this study – that there is not a clear cut performance difference under comprehensive sustainability analysis based on modal technology, rather comparable performance can be observed in both system sets. This study set out to understand how different modes may compare under sustainable mobility analysis – and while some general findings could be drawn from the data, the distribution of HR and LR systems throughout all indicators, categorical indices, and CSIs shows that either mode can attain good performance – or poor.

There is great complexity behind what allows a system to succeed – and this research reflects that mode may only be one factor among many. However, this research does share a general range of performance under many sustainability indicators that can be used in setting expectations for future mode planning.

This finding underscores the need for further research on sustainable mobility performance as well as on what factors shape performance. If a similar study would be repeated using global data, the findings may change based on the types of systems used and the contexts in which they operate. For example, high density Japanese cities served by HR may have much higher CSI values when compared to American public transit.

9.3.1 Limitations

While this study was able to provide commentary on the performance differences of transit modes and also present a new framework for analysis, there are limitations that could be addressed in future research. There were three major limitations to this study that hindered in depth or rigorous analysis of the different performance levels between the systems. These limitations were:

- **Scope**: – the scope of this study was to demonstrate the PTSMAP framework and use it to compare between the two system types.
- **Data:** – where possible within scope, additional analysis was attempted. However, given the need to utilize the NTD dataset, which is a high level data set that contains very little operational or city factor data, it is difficult to conduct regression analysis or utilize other tools to determine what shapes performance between the system sets.
- **Benchmarking:** In the actual analysis, benchmarking was conducted using values from within the data set – meaning it was assumed that benchmarking and comparing systems on a per pkm basis or through other normalization techniques would allow a 'best in operation' comparison to be conducted. While this process was effective for a first stage of research, further research using programming, modelling, and other techniques can seek out optimums to compare systems to. For example, MTA New York may have ranked highest overall and highest in some categories, however, these results may not be the best results possible for a sustainable transit system. This research presents the tool to conduct analysis and future research will need to identify clearer targets.

An additional limitation is that not all PTSMAP factors could be utilized in this implementation. However, in future studies these additional factors, including health impacts, can be implemented with system specific data. Another final limitation of the study is that it was reliant on set weights. While sensitivity testing demonstrated how different weighting at a category level could do to the results, future research should apply a weighting technique to all factor and category weights to demonstrate further how the results may change under a variety of scenarios.

A final limitation worth noting is that, as previously discussed, the tool's results need to be scrutinized with a level of critical thought. The literature review stated that tools to aid in research and decision making through composite indices should be easily interpreted, and arguably the final outputs of both methodologies are. Single digits representing a complex issue are – however – in their essence limited. By synthesizing competing issues into one single representation, meaning may be lost. Referring to the New York case, where MTA New York achieved high performance across all four categories but not uniform performance on all indicators.

While the results of this study show that some systems, such as MTA New York, achieve a degree of sustainability that is greater than others, when sustainability is broken up into the components measured in this implementation of the PTSMAP framework, it is seen there are strengths and weaknesses to each system. If the complete analysis is not represented, there is potential for tools such as this to be used to misrepresent a system as 'sustainable' rather than progressing towards sustainability. It is important to note that this tool is also important for identifying areas for improvement on sustainability and not just the single CSI score.

9.3.2 Future Research

This research can be expanded upon through the following key areas. The first is through increasing the scope and level of data for a select set of high and low systems to determine which variables impact factor performance. Such a study would greatly improve understanding of how systems perform under sustainable mobility analysis. This research should focus on operational/systemic factors, as well as urban factors.

A second expansion to the research should be to improve the set of indicators used. This research had to remove several factors, and also had to limit others. Future research can expand the PTSMAP framework to include other sustainable mobility factors for a more robust assessment of sustainable mobility, either for this dataset or another complementary data set. This will improve both the state of practice for sustainability assessment, but also improve understanding of sustainable mobility performance in an even more nuanced manner. Some factors include level of service or a more nuanced version of accessibility.

A third improvement would be to include life cycle assessment and capital costs, where possible, to better inform not just how systems compare under sustainable mobility from an operations lens, but also from a construction and operations lens. Such a study would complement existing literature on life cycle analysis of transport infrastructure and further inform the debate on what it means to have a truly sustainable transportation system. The focus of this study is on the operation of transit in the provision of mobility. In order to provide a holistic view point, future work could also analyze construction and maintenance emissions, pollution, costs, system effectiveness and social impacts that are not included in this study.

Fourth, many factors stand in for rider experience, however, this section of the research could be expanded in future revisions. Sustainable transportation needs to meet user needs. In transportation planning and research the level of service concept is used to understand how well a transit system reflect user needs. In this study methodology, costs and accessibility were included, but future studies could delve deeper and consider a more nuanced reflection on passenger satisfaction as part of sustainability.

Next, this framework does not utilize a nuanced accessibility factor as explored in the literature review. Whole studies have been dedicated to exploring how transit improves access to residential, service, activity, and employment centres. Due to the scope of this research, these factors are not included in this study. Future research could use GIS frameworks or other tools to better explore accessibility.

Additionally, improving the aggregation, normalization, and comparison of data in methods 1, 2, and 3 or perhaps through an additional method can remove the biases that occur and limit CSI scores that may be artificially high.. Further development of the statistical and mathematical techniques used in this PTSMAP framework, including an expansion of the methods suggested by Jeon (2007) and Haghshenas & Vaziri (2012) to mitigate extreme values as well as create a CSI that is not as influenced by high and low performance. Additionally, the inclusion of AHP or other decision tools as an explicit part of the framework may improve its rigour and applicability in research and decision making.

In the literature review, transit oriented development and land use integration are discussed as key drivers of sustainable mobility and sustainable urbanization. However, in this methodology they are absent. As this research had to focus on select factors and tools, some depth of sustainability, such as an investigation into transit oriented development, should be included in future research. Future studies should include how specific transit systems integrate into density, land use planning, and long range planning in order to ensure sustainable mobility.

Finally, this study could be expanded through global comparison. Utilizing data from other jurisdictions to compare performance from different urban contexts and operational configurations, including BRT, would greatly improve the applicability and refinement of these techniques. Further, developing a ranking scheme or characterization scheme for systems based on mode and geographic context (high density, low density) to aid in sustainability characterization would further improve this research.

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Appendix A: Inputs

	System ID	Operator Name	Directional Route km	Passenger KM	Unlinked Passenger Trips	Train Rev Hours	Passenger KM	Kwh Propulsion	Total Operating Cost (2010 USD)	Fare revenue
Heavy Rail Systems (HR)	1003	Massachusetts Bay Transportation Authority	122.792642	776,511,917.15	139,039,529.00	223,844.00	2,633,593.18	197,321,627.00	$306,460,723.00	$153,168,117.00
	2008	MTA New York City Transit	784.55	15626406910.53	2439158966.00	2111734.00	50256532.28	1715052000	$3,345,934,576.00	$2,398,466,039.00
	2098	Port Authority Trans-Hudson Corporation	46.03	565834473.03	82994189.00	95043.00	1882448.22	103083570	$297,889,695.00	$104,673,000.00
	2099	Staten Island Rapid Transit Operating Authority	46.03	72546267.87	7635882.00	28526.00	266532.45	22533462	$35,631,028.00	$6,522,074.00
	3019	Southeastern Pennsylvania Transportation Authority	120.54	679340481.33	95229240.00	166723.00	2279861.85	150897021	$166,097,224.00	$84,909,232.00
	3030	Washington Metropolitan Area Transit Authority	340.86	2632827564.69	287304340.00	428515.00	8976011.77	491982667	$787,299,552.00	$487,832,729.00
	3034	Maryland Transit Administration	47.31	92175770.87	13363903.00	42727.00	312924.90	46294385	$53,537,291.00	$11,468,806.00
	4022	Metropolitan Atlanta Rapid Transit Authority	154.59	793735472.95	77732006.00	148856.00	2537344.99	95342672	$171,509,427.00	$58,775,169.00
	4034	Miami-Dade Transit	72.48	206620341	1737155	43080.	70368	7062237	$76,188,170.	$17,827,407.

	System ID	Operator Name	Directional Route km	Passenger KM	Unlinked Passenger Trips	Train Rev Hours	Passenger KM	Kwh Propulsion	Total Operating Cost (2010 USD)	Fare revenue
				.43	3.00	00	2.31	0	00	00
	5015	The Greater Cleveland Regional Transit Authority	61.28	41664821.25	3657501.00	46583.00	128708.58	25827150	$22,552,608.00	$4,065,336.00
	5066	Chicago Transit Authority	334.49	2086497431.46	210849074.00	604261.00	6770042.76	407659190	$451,039,566.00	$239,349,891.00
	9003	San Francisco Bay Area Rapid Transit District	336.42	2238446544.18	108297950.00	252091.00	7388487.99	281721374	$463,074,086.00	$331,361,008.00
	9154	Los Angeles County Metropolitan Transportation Authority	51.34	373263626.35	47905917.00	60648.00	1157762.41	86444000	$90,320,275.00	$34,983,345.00
Light Rail (LR)	0008	Tri-County Metropolitan Transportation District of Oregon	180.83	335996664.62	42452640.00	305050.00	261194.27	53556304	$106,374,746.00	$36,908,552.00
	0040	Central Puget Sound Regional Transit Authority	49.57	90734399.30	7831905.00	71078.00	857472.45	13327909	$41,377,642.00	$9,608,740
	1003	Massachusetts Bay Transportation Authority	82.08	249781103.75	65471593.00	346281.00	90232.48	52076193	$140,761,337.00	$69,637,279.00
	2004	Niagara Frontier Transportation Authority	19.96	26216383.56	6215596.00	31992.00	75334.81	9273194	$23,571,179.00	$4,496,914.00
	3022	Port Authority of Allegheny County	76.23	54111495.43	7006477.00	91102.00	278834.25	31232044	$50,135,809.00	$7,915,403.00

System ID	Operator Name	Directional Route km	Passenger KM	Unlinked Passenger Trips	Train Rev Hours	Passenger KM	Kwh Propulsion	Total Operating Cost (2010 USD)	Fare revenue
3034	Maryland Transit Administration	92.70	87737122.64	8070249.00	84579.00	4028.18	33758160	$39,400,273.00	$7,012,729.00
4008	Charlotte Area Transit System	30.51	27556543.75	3250020.00	28751.00	2875.89	6699660	$16,042,893.00	$3,211,891.00
5015	The Greater Cleveland Regional Transit Authority	48.89	21905080.79	2315662.00	42307.00	267322.64	11148011	$12,643,996.00	$2,573,873.00
5027	Metro Transit	39.82	89064253.60	10455860.00	69586.00	127026.82	17220000	$25,736,123.00	$10,361,080.00
6008	Metropolitan Transit Authority of Harris County, Texas	23.83	38893743.76	10616292.00	64492.00	68799.29	6913813	$14,817,148.00	$5,787,387.00
6056	Dallas Area Rapid Transit	156.40	201816091.38	17799186.00	163376.00	685039.71	70181785	$111,987,383.00	$14,133,759.00
7006	Bi-State Development Agency	146.55	220250152.49	15828981.00	116669.00	310514.11	36302117	$53,945,130.00	$17,020,608.00
8001	Utah Transit Authority	63.36	92100283.17	13400546.00	84644.00	732360.74	23196953	$28,006,024.00	$10,413,625.00
8006	Denver Regional Transportation District	112.65	224368796.34	20087726.00	183865.00	263099.73	46339256	$71,424,851.00	$22,230,716.00
9013	Santa Clara Valley Transportation Authority	130.29	80467437.74	9749879.00	133236.00	689116.17	22358361	$56,685,665.00	$8,610,634.00
9015	San Francisco Municipal Railway	133.74	211415192.93	49396925.00	461642.00	447184.09	53800267	$169,225,292.00	$38,087,880.00

System ID	Operator Name	Directional Route km	Passenger KM	Unlinked Passenger Trips	Train Rev Hours	Passenger KM	Kwh Propulsion	Total Operating Cost (2010 USD)	Fare revenue
9019	Sacramento Regional Transit District	118.74	132771325.70	15317881.00	81226.00	900506.20	34946640	$47,846,225.00	$14,452,250.00
9026	San Diego Metropolitan Transit System	174.45	300156896.17	30468981.00	177434.00	96925.72	38451291	$60,912,964.00	$33,049,792.00
9154	Los Angeles County Metropolitan Transportation Authority	194.92	536448373.64	46409075.00	187402.00	420417.54	95971346	$167,914,954.00	$30,725,008.00
9209	Valley Metro Rail, Inc.	63.05	141077568.79	12112733.00	89316.00	420417.54	20967081	$32,964,700.00	$9,256,913.00

Appendix B: Energy Emissions Table

Code	State	CO2	CH4	N2O	SO2	Nox	Hg
		ilbs/kwh					
AL	Alabama	1.399	2.39E-05	2.28E-05	0.006671	0.001867	4.21E-08
AK	Alaska	1.199	2.77E-05	7.24E-06	0.001237	0.003909	1.80E-09
AZ	Arizona	1.246	1.68E-05	1.65E-05	0.001078	0.001596	1.56E-08
AR	Arkansas	1.268	2.68E-05	2.20E-05	0.003029	0.00157	2.25E-08
CA	California	0.598	3.14E-05	4.48E-06	0.000432	0.000409	2.11E-09
CO	Colorado	1.91	2.42E-05	2.81E-05	0.002678	0.002726	1.73E-08
CT	Connecticut	0.73	6.30E-05	1.23E-05	0.002474	0.000869	1.67E-08
DE	Delaware	1.907	2.60E-05	2.72E-05	0.008444	0.002784	4.21E-08
DC	District of Columbia	2.94	1.26E-04	2.53E-05	0.010511	0.004487	N/A
FL	Florida	1.329	4.34E-05	1.71E-05	0.003771	0.002132	1.10E-08
GA	Georgia	1.483	2.10E-05	2.44E-05	0.009572	0.001644	2.90E-08
HI	Hawaii	1.632	1.09E-04	2.23E-05	0.008315	0.005017	1.23E-08
ID	Idaho	0.148	1.43E-05	2.63E-06	0.000266	0.000146	N/A
IL	Illinois	1.17	1.37E-05	1.93E-05	0.003071	0.001295	4.51E-08
IN	Indiana	2.168	2.51E-05	3.60E-05	0.011687	0.003265	4.76E-08
IA	Iowa	1.883	2.22E-05	3.12E-05	0.006074	0.002429	5.34E-08
KS	Kansas	1.819	2.12E-05	3.00E-05	0.004884	0.002974	4.69E-08
KY	Kentucky	2.215	2.59E-05	3.74E-05	0.00827	0.003814	3.96E-08
LA	Louisiana	1.144	2.45E-05	1.23E-05	0.002047	0.001431	1.34E-08
ME	Maine	0.558	2.07E-04	2.98E	0.00196	0.0012	2.96E

		ilbs/kwh					
Code	State	CO2	CH4	N2O	SO2	Nox	Hg
				-05	9		-09
MD	Maryland	1.414	3.49E-05	2.45E-05	0.012732	0.002436	4.10E-08
MA	Massachusetts	1.267	6.85E-05	1.73E-05	0.003965	0.001073	1.58E-08
MI	Michigan	1.498	3.00E-05	2.55E-05	0.006527	0.002154	3.28E-08
MN	Minnesota	1.609	4.51E-05	2.91E-05	0.003761	0.003214	3.06E-08
MS	Mississippi	1.305	2.32E-05	1.67E-05	0.003049	0.002096	1.39E-08
MO	Missouri	1.884	2.19E-05	3.12E-05	0.006278	0.00253	4.54E-08
MT	Montana	1.706	2.13E-05	2.91E-05	0.003245	0.003256	3.83E-08
NE	Nebraska	1.509	1.75E-05	2.50E-05	0.004435	0.002667	2.35E-08
NV	Nevada	1.228	1.97E-05	1.06E-05	0.000562	0.001499	1.58E-08
NH	NewHampshire	0.701	6.58E-05	1.51E-05	0.00419	0.000681	2.64E-09
NJ	NewJersey	0.74	2.53E-05	9.15E-06	0.002816	0.000772	1.40E-08
NM	NewMexico	1.891	2.33E-05	2.90E-05	0.001567	0.004223	6.75E-08
NY	NewYork	0.796	2.83E-05	8.97E-06	0.002184	0.000824	1.16E-08
NC	NorthCarolina	1.305	2.00E-05	2.22E-05	0.0064	0.001118	2.86E-08
ND	NorthDakota	2.358	2.55E-05	3.79E-05	0.009248	0.004778	7.56E-08
OH	Ohio	1.911	2.29E-05	3.21E-05	0.013259	0.003313	5.10E-08
OK	Oklahoma	1.57	2.28E-05	1.93E-05	0.003929	0.002543	2.93E-08
OR	Oregon	0.434	1.83E-05	5.32E-06	0.000669	0.000542	3.81E-09
PA	Pennsylvania	1.277	2.52E-05	2.11E-05	0.009934	0.001909	5.16E-08
RI	RhodeIsland	0.96	1.91E-05	1.93E-06	0.000031	0.00025	N/A
SC	SouthCarolina	0.959	1.69E-05	1.63E-05	0.003644	0.001007	1.26E-08

		ilbs/kwh					
Code	State	CO2	CH4	N2O	SO2	Nox	Hg
SD	SouthDakota	1.297	1.57E-05	2.03E-05	0.003634	0.004114	1.50E-08
TN	Tennessee	1.434	1.88E-05	2.46E-05	0.005388	0.002394	3.00E-08
TX	Texas	1.382	2.01E-05	1.57E-05	0.002631	0.000907	2.59E-08
UT	Utah	2.046	2.47E-05	3.24E-05	0.001399	0.003633	8.03E-09
VT	Vermont	0.004	7.96E-05	1.06E-05	0.000016	0.000242	N/A
VA	Virginia	1.203	3.79E-05	2.05E-05	0.005859	0.001994	1.68E-08
WA	Washington	0.274	1.04E-05	4.59E-06	0.000132	0.000322	6.98E-09
WV	WestVirginia	2.079	2.37E-05	3.53E-05	0.009198	0.003535	5.66E-08
WI	Wisconsin	1.682	2.85E-05	2.81E-05	0.005003	0.001985	3.93E-08
WY	Wyoming	2.366	2.70E-05	4.00E-05	0.004033	0.003804	4.30E-08

Source (Leonardo Academy Inc., 2011)

Appendix C: Income Per Capita

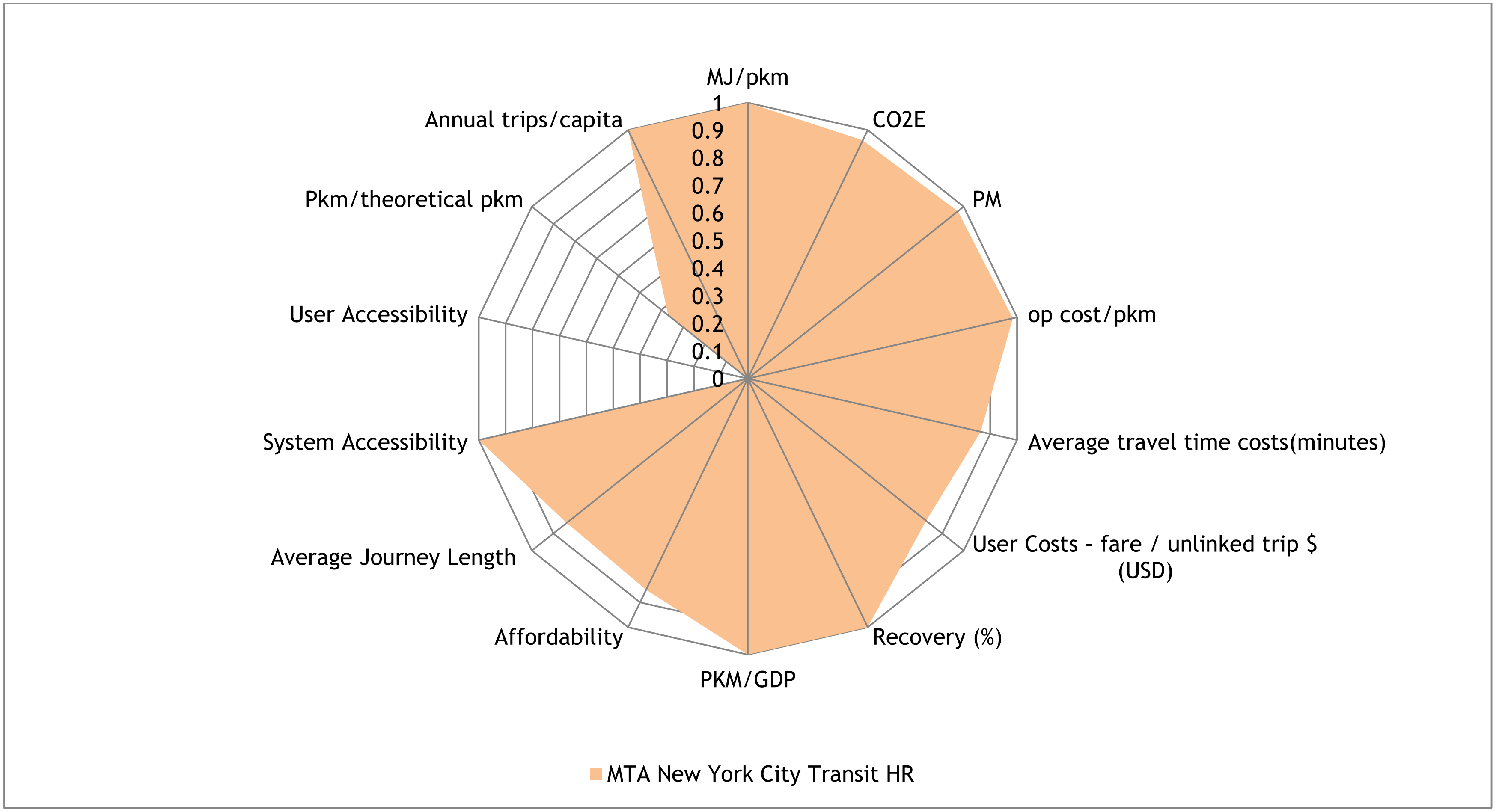
MSA	Income Per Capita (2010 USD)
Atlanta-Sandy Springs-Marietta, GA Metro Area	26333
Baltimore-Towson, MD Metro Area	32568
Boston-Cambridge-Quincy, MA-NH Metro Area	35999
Buffalo-Niagara Falls, NY Metro Area	25178
Charlotte-Gastonia-Rock Hill, NC-SC Metro Area	26657
Chicago-Joliet-Naperville, IL-IN-WI Metro Area	28630
Cleveland, TN Metro Area	19212
Dallas-Fort Worth-Arlington, TX Metro Area	27016
Denver-Aurora-Broomfield, CO Metro Area	30891
Houston-Sugar Land-Baytown, TX Metro Area	26440
Los Angeles-Long Beach-Santa Ana, CA Metro Area	27051
New York-Northern New Jersey-Long Island, NY-NJ-PA Metro Area	33208
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD Metro Area	30250
Phoenix-Mesa-Glendale, AZ Metro Area	24809
Pittsburgh, PA Metro Area	27075
Portland-Vancouver-Hillsboro, OR-WA Metro Area	27451
Sacramento--Arden-Arcade--Roseville, CA Metro Area	26992
St. Louis, MO-IL Metro Area	27242
Salt Lake City, UT Metro Area	24006
San Diego-Carlsbad-San Marcos, CA Metro Area	28498
San Francisco-Oakland-Fremont, CA Metro Area	37693
San Jose-Sunnyvale-Santa Clara, CA Metro Area	37177
Seattle-Tacoma-Bellevue, WA Metro Area	32401
Washington-Arlington-Alexandria, DC-VA-MD-WV Metro Area	40528

(U.S. Census Bureau, 2013)

Appendix D: Method 3 Sustainability Analysis Graphs

This appendix contains graphs for each system analyzed in this research thesis. For reference, these systems are:

Operator	EI	EcI	SI	SeI	CSI
MTA New York City Transit HR	0.977	0.935	0.672	0.685	0.817
Los Angeles County Metropolitan Transportation Authority HR	0.887	0.642	0.663	0.505	0.674
Chicago Transit Authority HR	0.840	0.653	0.566	0.318	0.594
San Francisco Municipal Railway LR	0.868	0.385	0.948	0.177	0.594
Los Angeles County Metropolitan Transportation Authority LR	0.933	0.504	0.618	0.309	0.591
Tri-County Metropolitan Transportation District of Oregon LR	0.955	0.545	0.658	0.202	0.590
Metropolitan Transit Authority of Harris County, Texas LR	0.868	0.630	0.749	0.090	0.584
San Diego Metropolitan Transit System LR	0.977	0.623	0.592	0.098	0.572
Southeastern Pennsylvania Transportation Authority HR	0.765	0.690	0.536	0.291	0.571
Metropolitan Atlanta Rapid Transit Authority HR	0.918	0.659	0.624	0.067	0.567
Massachusetts Bay Transportation Authority HR	0.784	0.652	0.661	0.076	0.543
Washington Metropolitan Area Transit Authority HR	0.620	0.717	0.603	0.228	0.542
Port Authority Trans-Hudson Corporation HR	0.905	0.502	0.496	0.241	0.536
Utah Transit Authority LR	0.710	0.583	0.671	0.157	0.530
Valley Metro Rail, Inc. LR	0.913	0.438	0.592	0.139	0.520
Massachusetts Bay Transportation Authority LR	0.839	0.548	0.553	0.141	0.520
San Francisco Bay Area Rapid Transit District HR	0.979	0.594	0.301	0.198	0.518
Metro Transit LR	0.805	0.530	0.635	0.095	0.516
Sacramento Regional Transit District LR	0.860	0.546	0.620	0.033	0.515
Bi-State Development Agency LR	0.825	0.531	0.526	0.115	0.499
Niagara Frontier Transportation Authority LR	0.733	0.383	0.729	0.127	0.493
Central Puget Sound Regional Transit Authority LR	0.973	0.389	0.577	0.019	0.490
Santa Clara Valley Transportation Authority LR	0.847	0.353	0.676	0.066	0.486
Denver Regional Transportation District LR	0.786	0.481	0.585	0.045	0.474
Charlotte Area Transit System LR	0.775	0.417	0.614	0.023	0.457
Miami-Dade Transit HR	0.661	0.512	0.545	0.043	0.440
Staten Island Rapid Transit Operating Authority, dba: MTA Staten Island Railway HR	0.776	0.451	0.420	0.073	0.430
Dallas Area Rapid Transit LR	0.658	0.351	0.601	0.103	0.428
Maryland Transit Administration LR	0.503	0.426	0.621	0.041	0.398
Maryland Transit Administration HR	0.325	0.510	0.680	0.009	0.381
Port Authority of Allegheny County LR	0.251	0.256	0.604	0.045	0.289
The Greater Cleveland Regional Transit Authority HR	0.000	0.380	0.458	0.202	0.260
The Greater Cleveland Regional Transit Authority LR	0.195	0.356	0.345	0.134	0.257


MJ/pkm
CO2E
PM
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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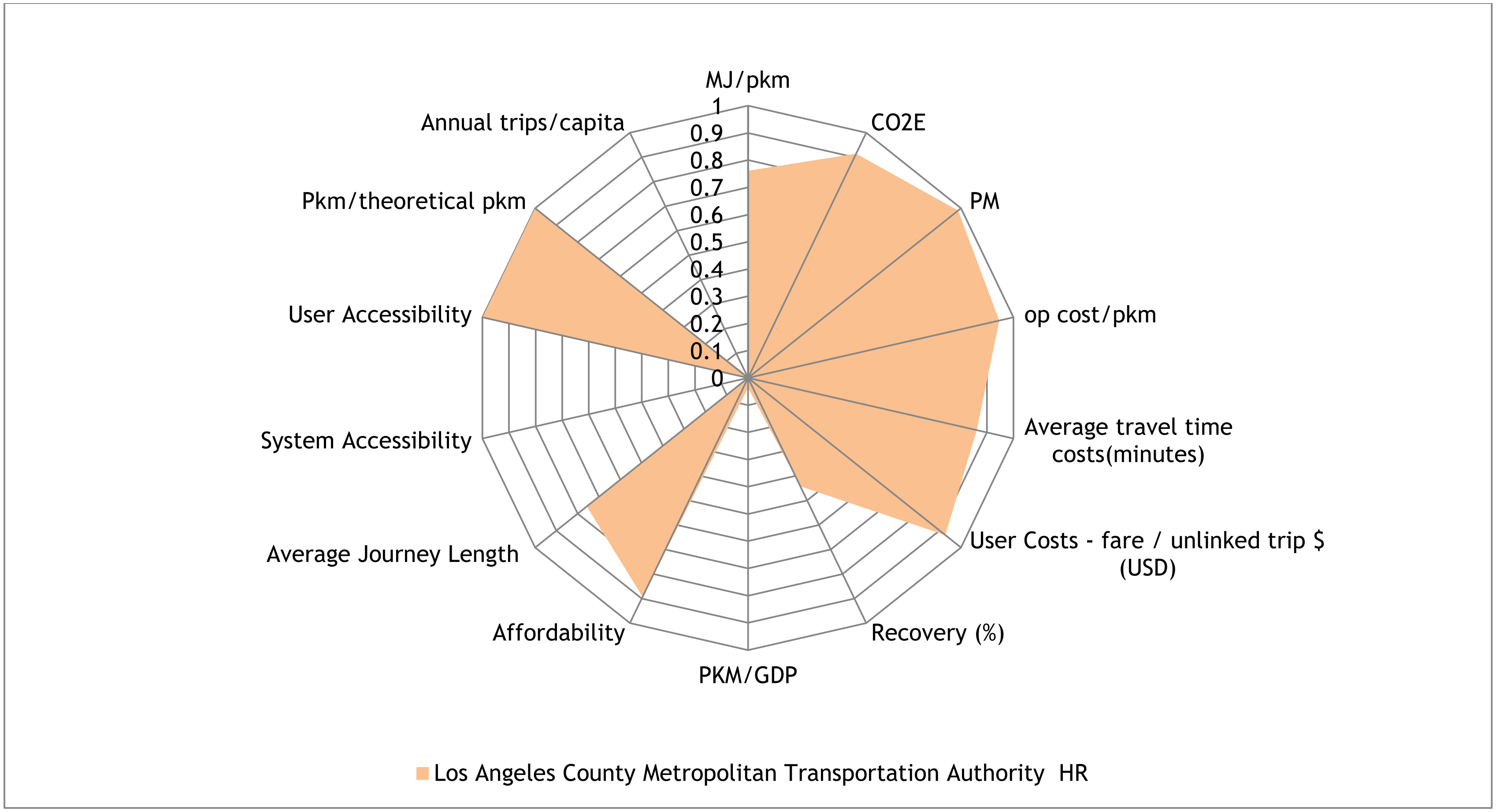
MTA New York City Transit HR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PM
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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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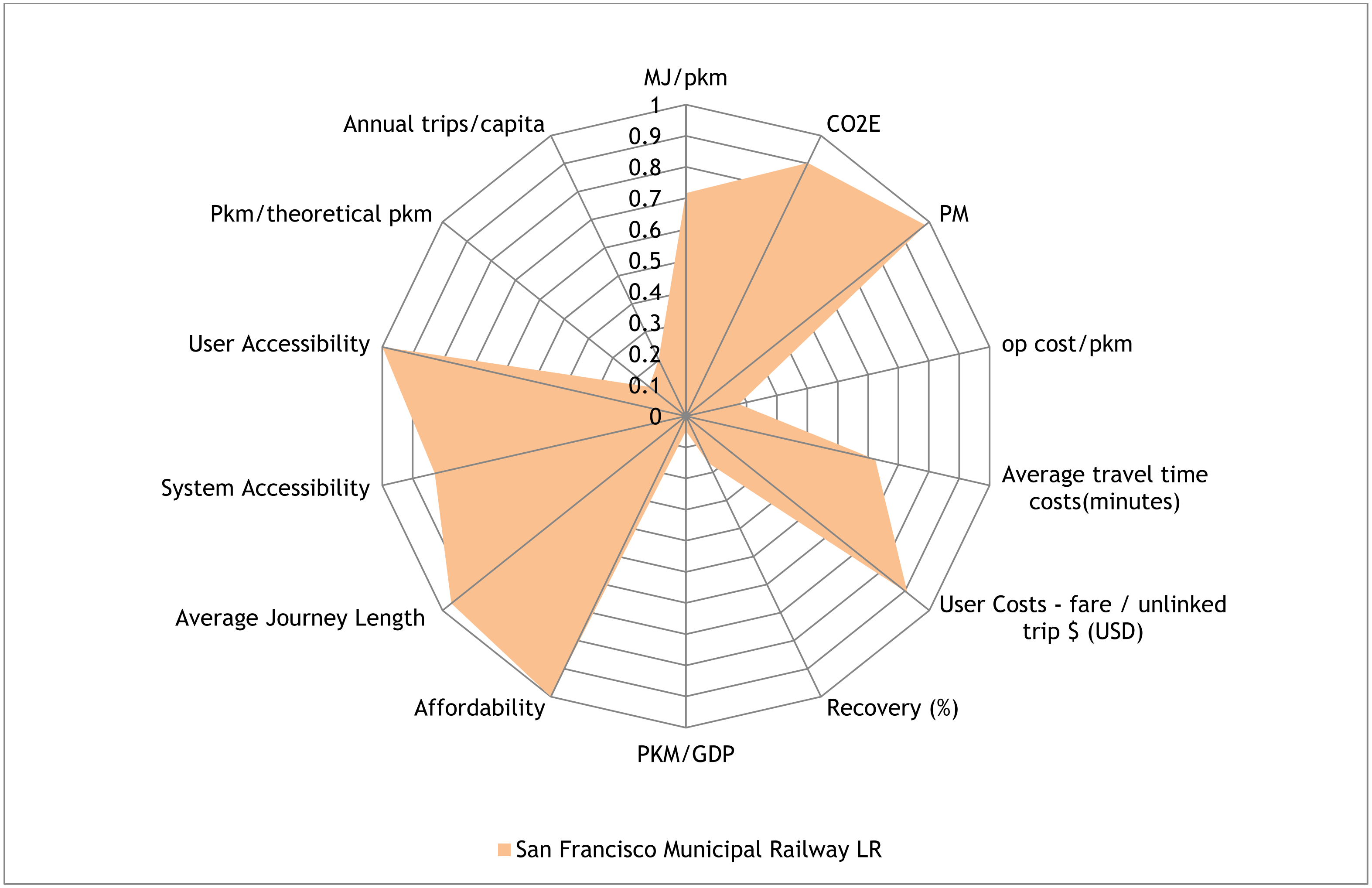
Los Angeles County Metropolitan Transportation Authority HR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CO2E
PM
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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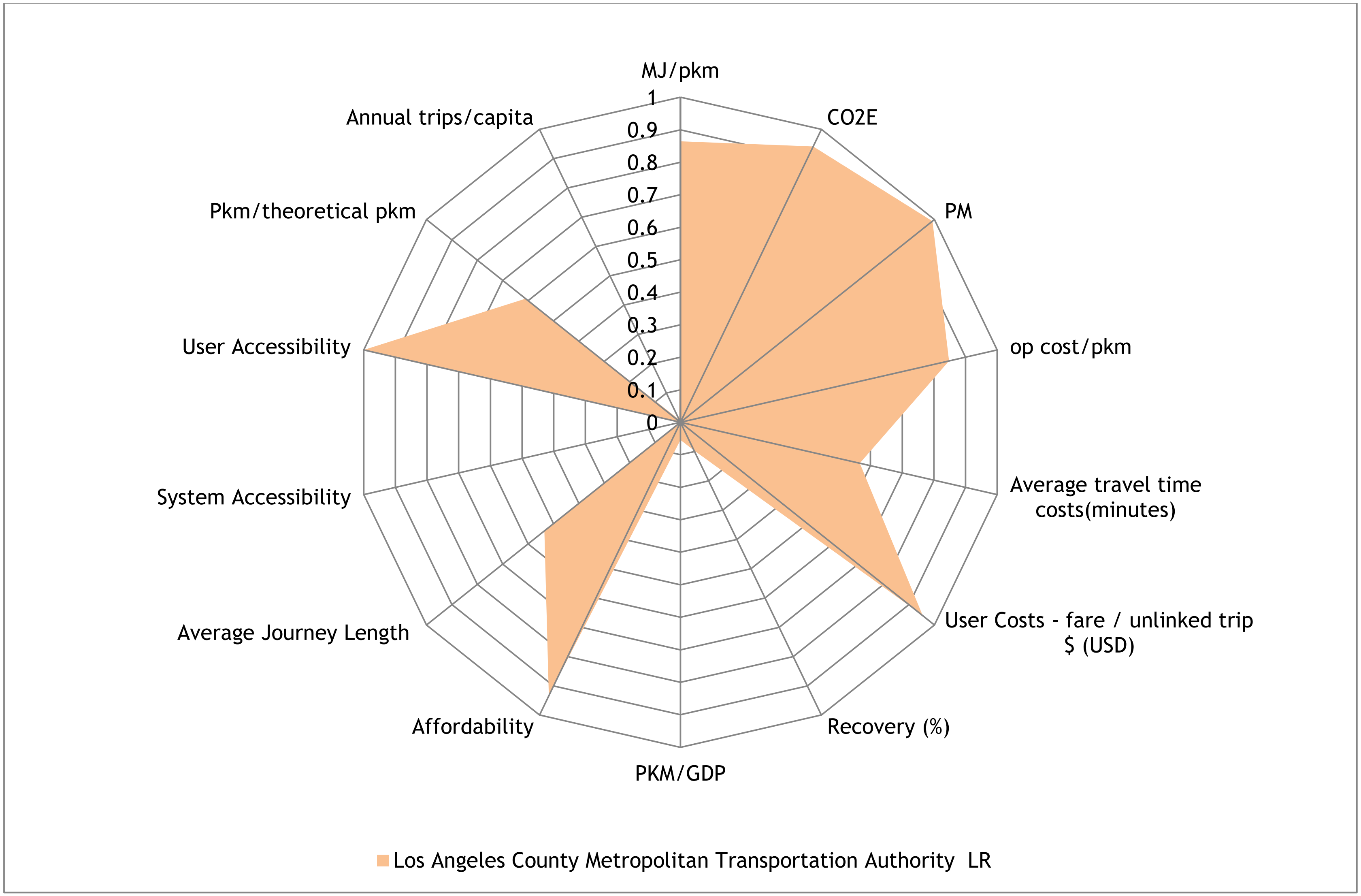
San Francisco Municipal Railway LR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PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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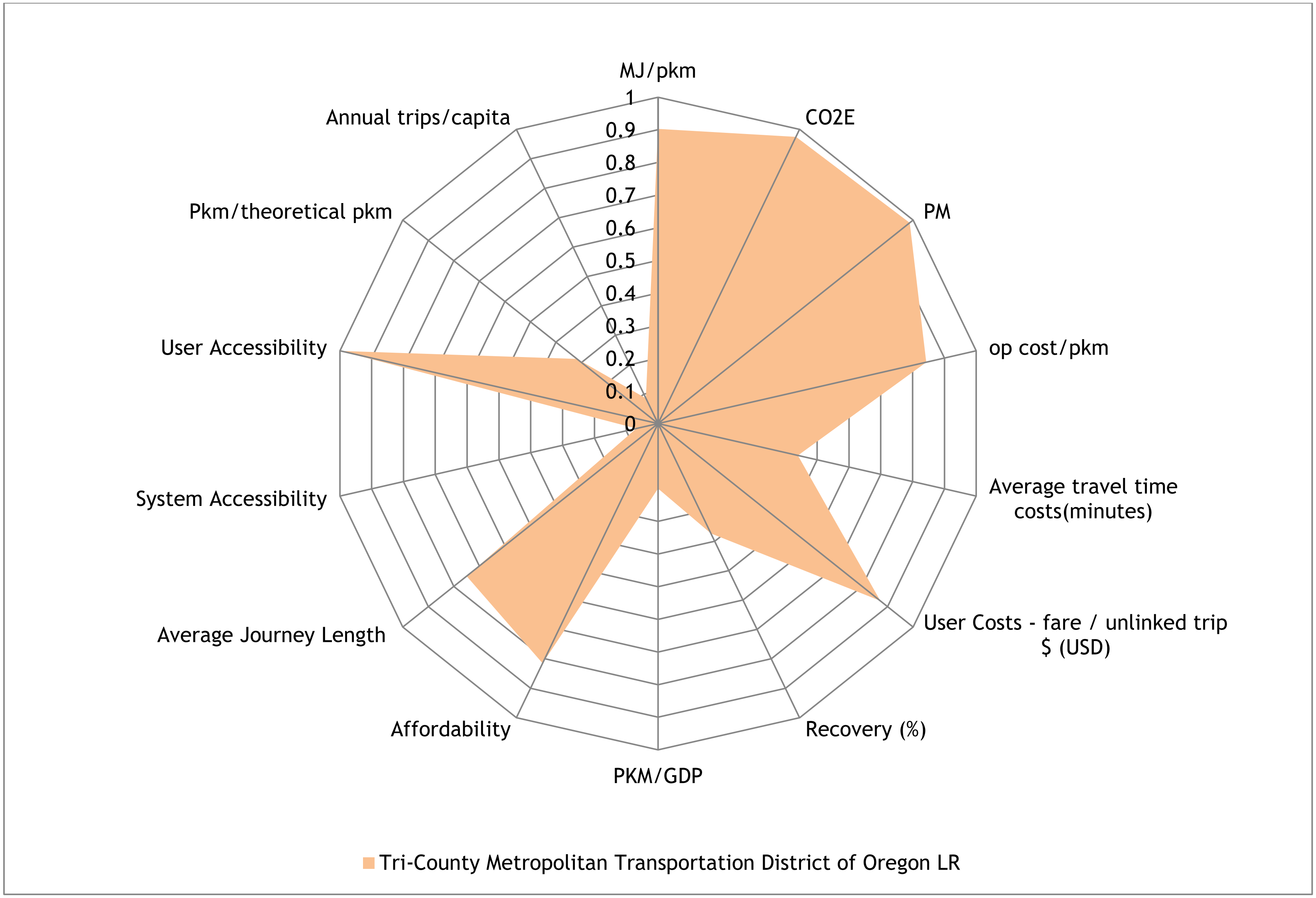
Los Angeles County Metropolitan Transportation Authority LR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Average travel time costs(minutes)
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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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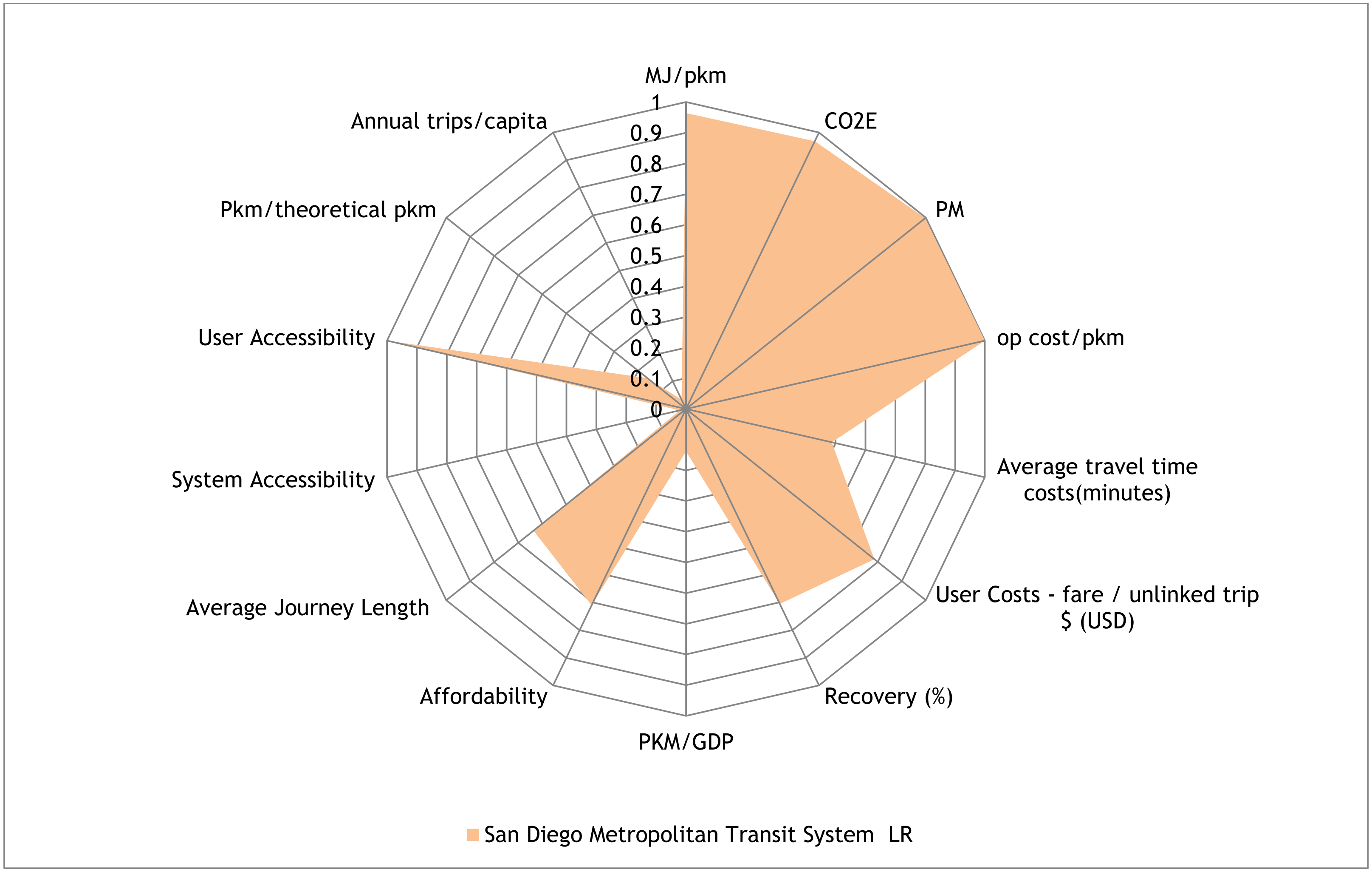
Tri-County Metropolitan Transportation District of Oregon LR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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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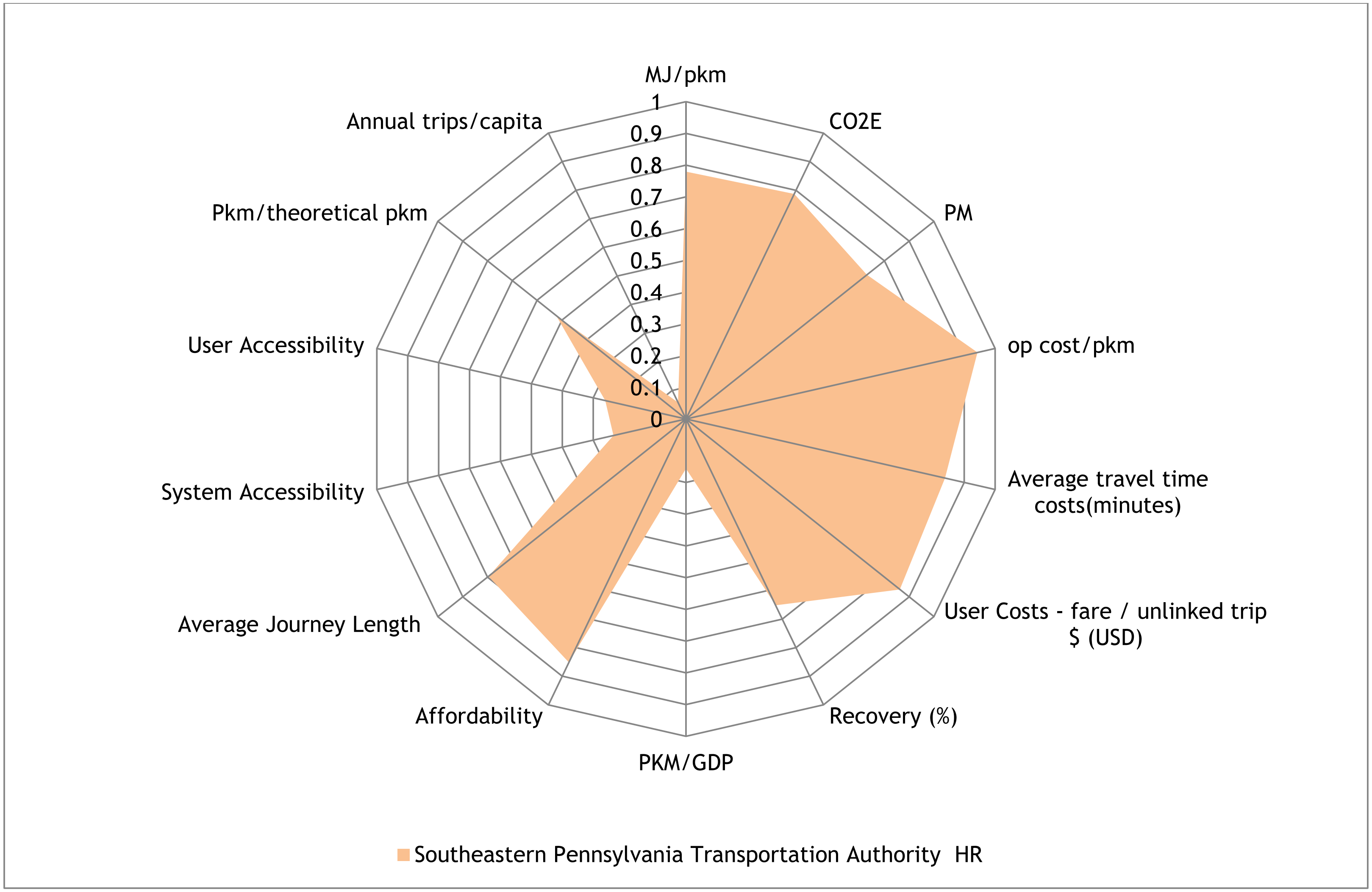
San Diego Metropolitan Transit System LR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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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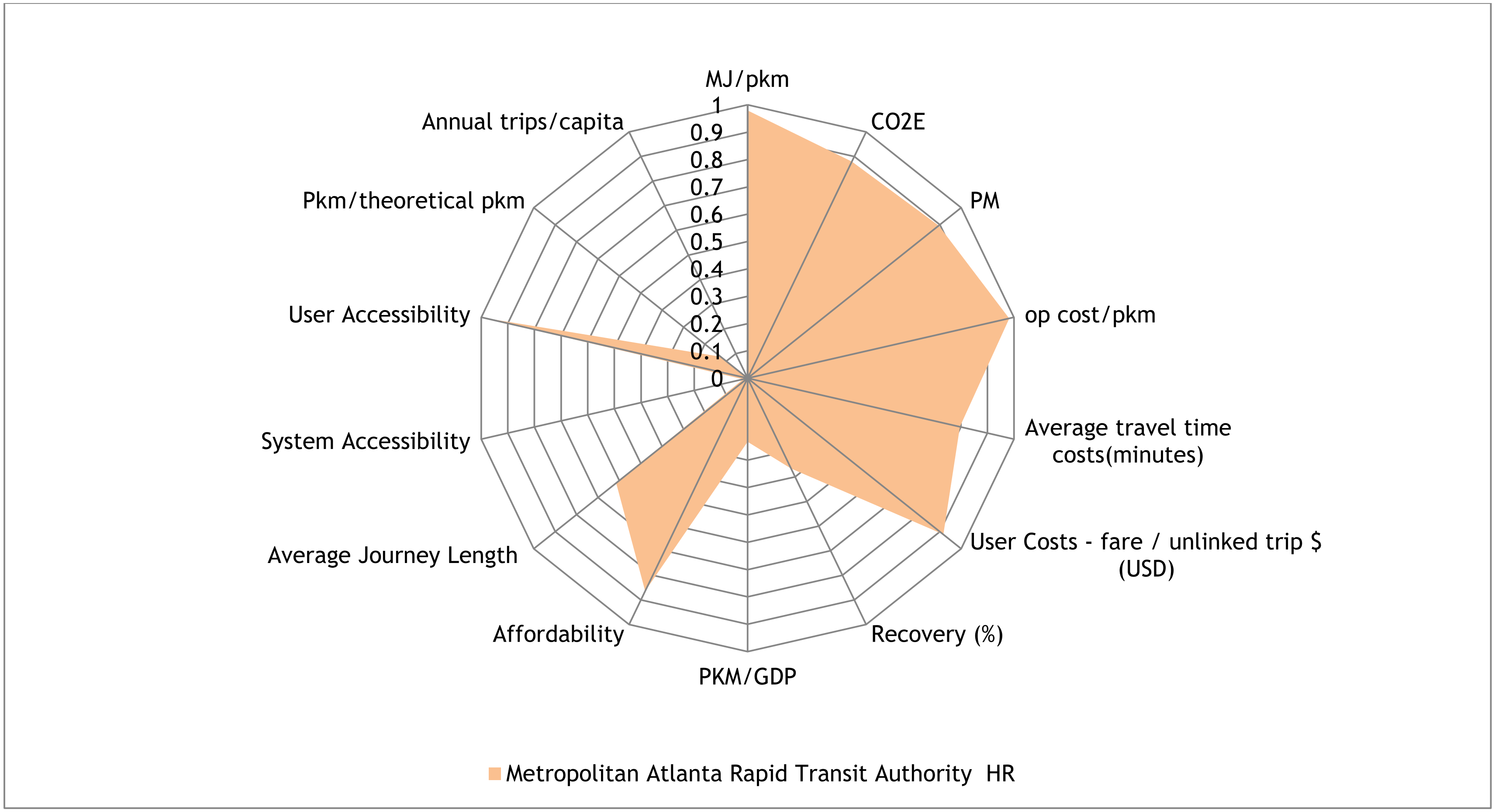
Southeastern Pennsylvania Transportation Authority HR


MJ/pkm
CO2E
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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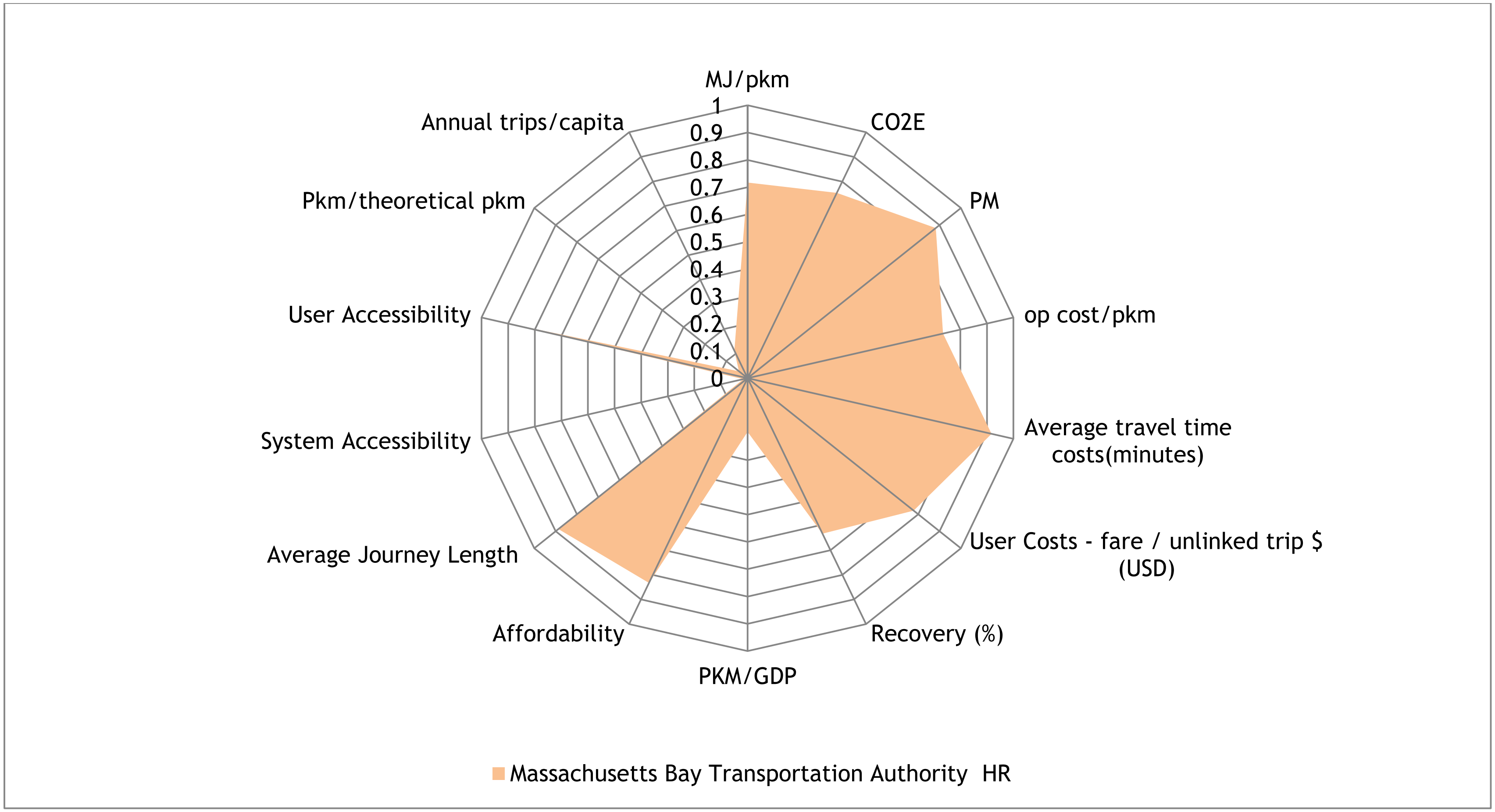
Metropolitan Atlanta Rapid Transit Authority HR


MJ/pkm
CO2E
PM
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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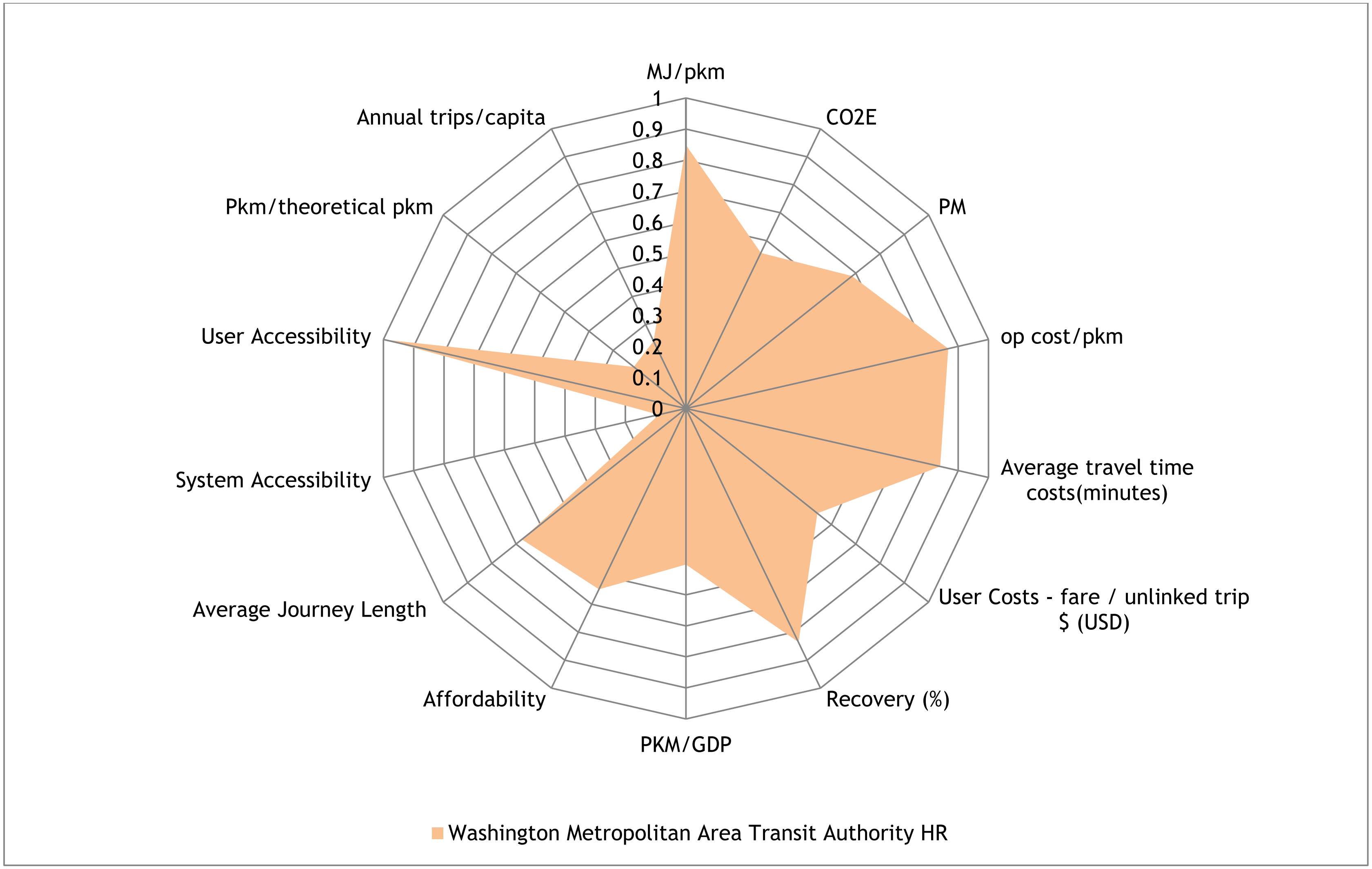
Massachusetts Bay Transportation Authority HR


MJ/pkm
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PM
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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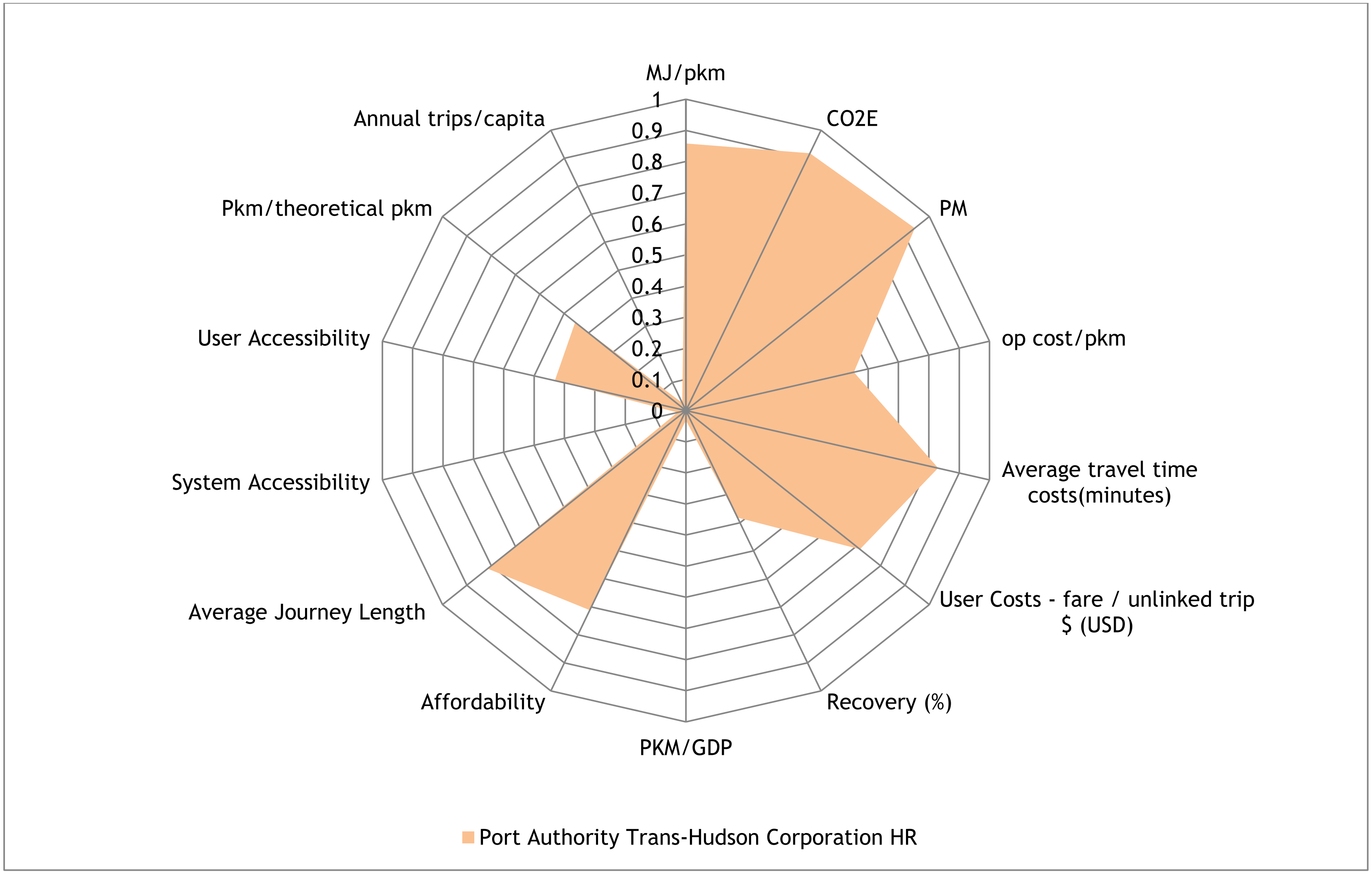
Washington Metropolitan Area Transit Authority HR


MJ/pkm
CO2E
PM
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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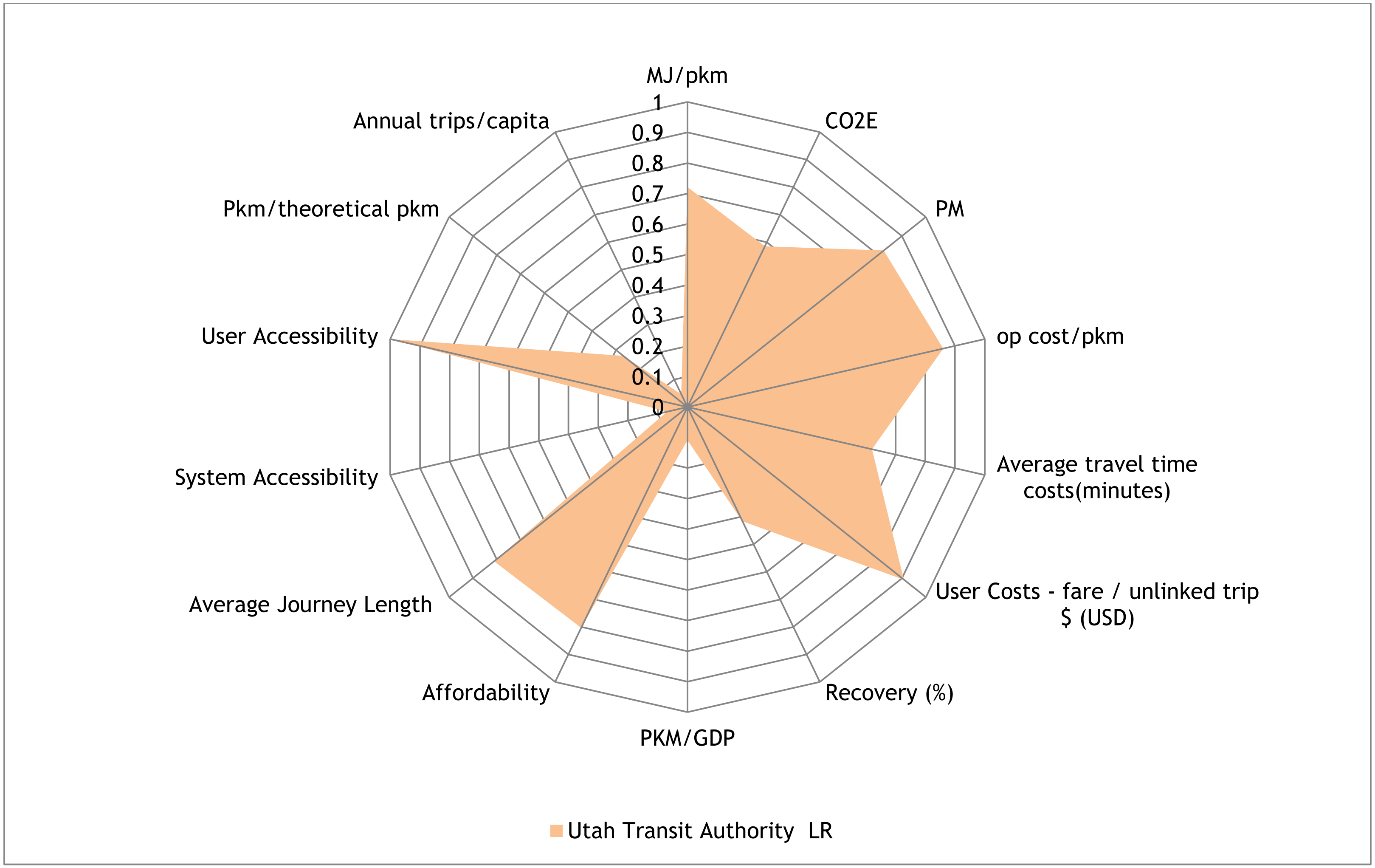
Port Authority Trans-Hudson Corporation HR


MJ/pkm
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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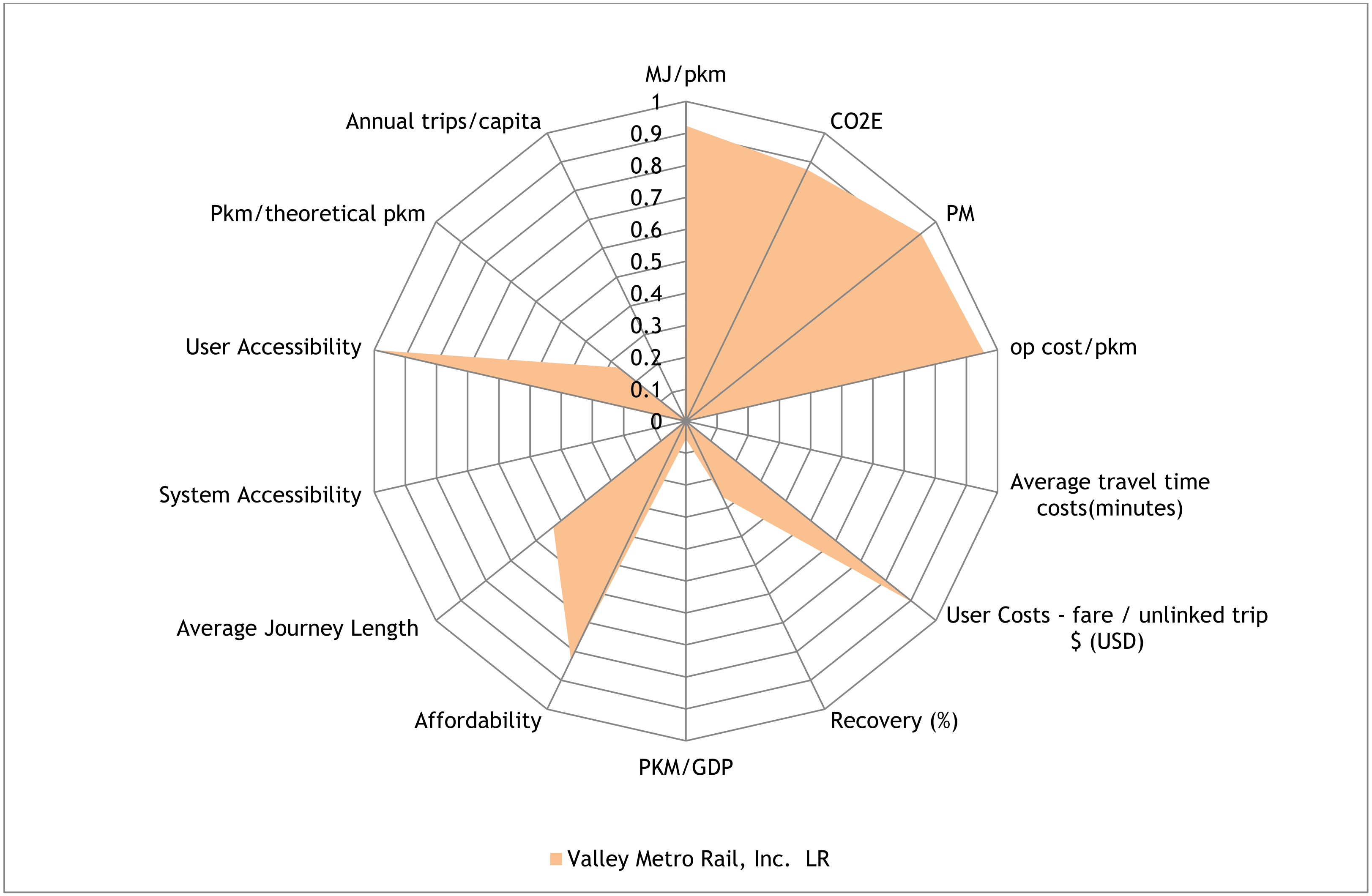
Utah Transit Authority LR


MJ/pkm
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Average travel time costs(minutes)
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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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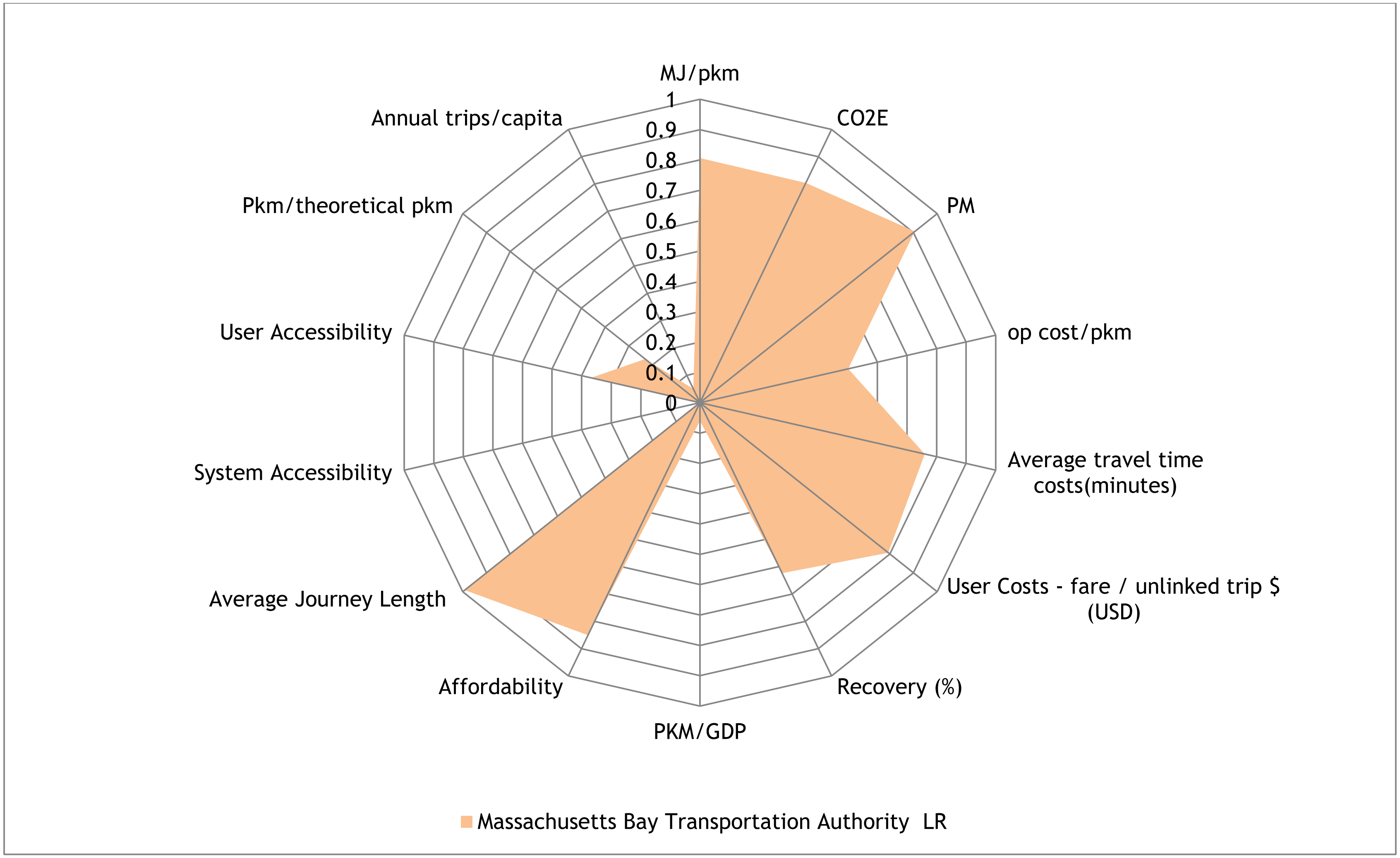
Valley Metro Rail, Inc. LR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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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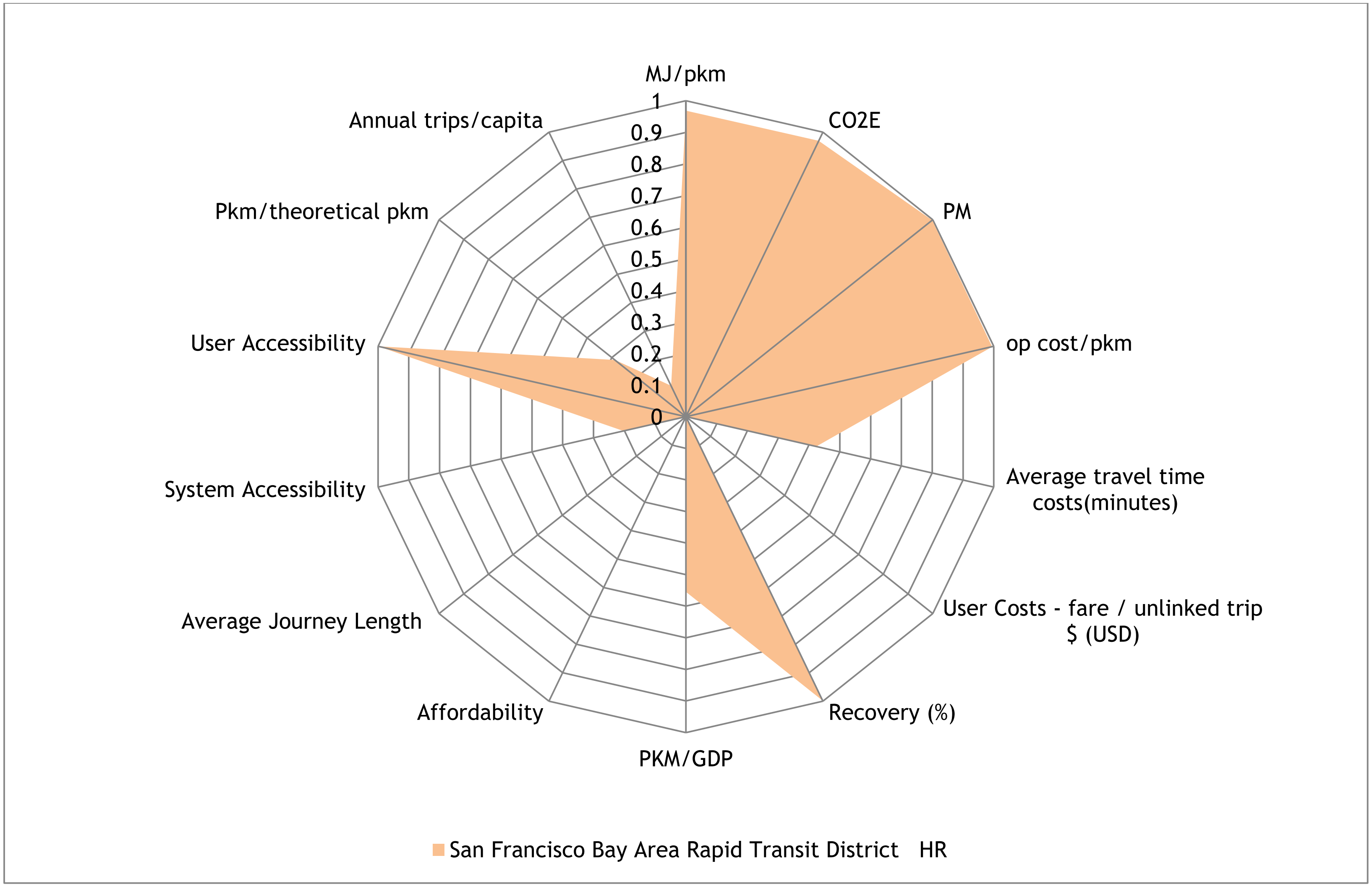
Massachusetts Bay Transportation Authority LR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User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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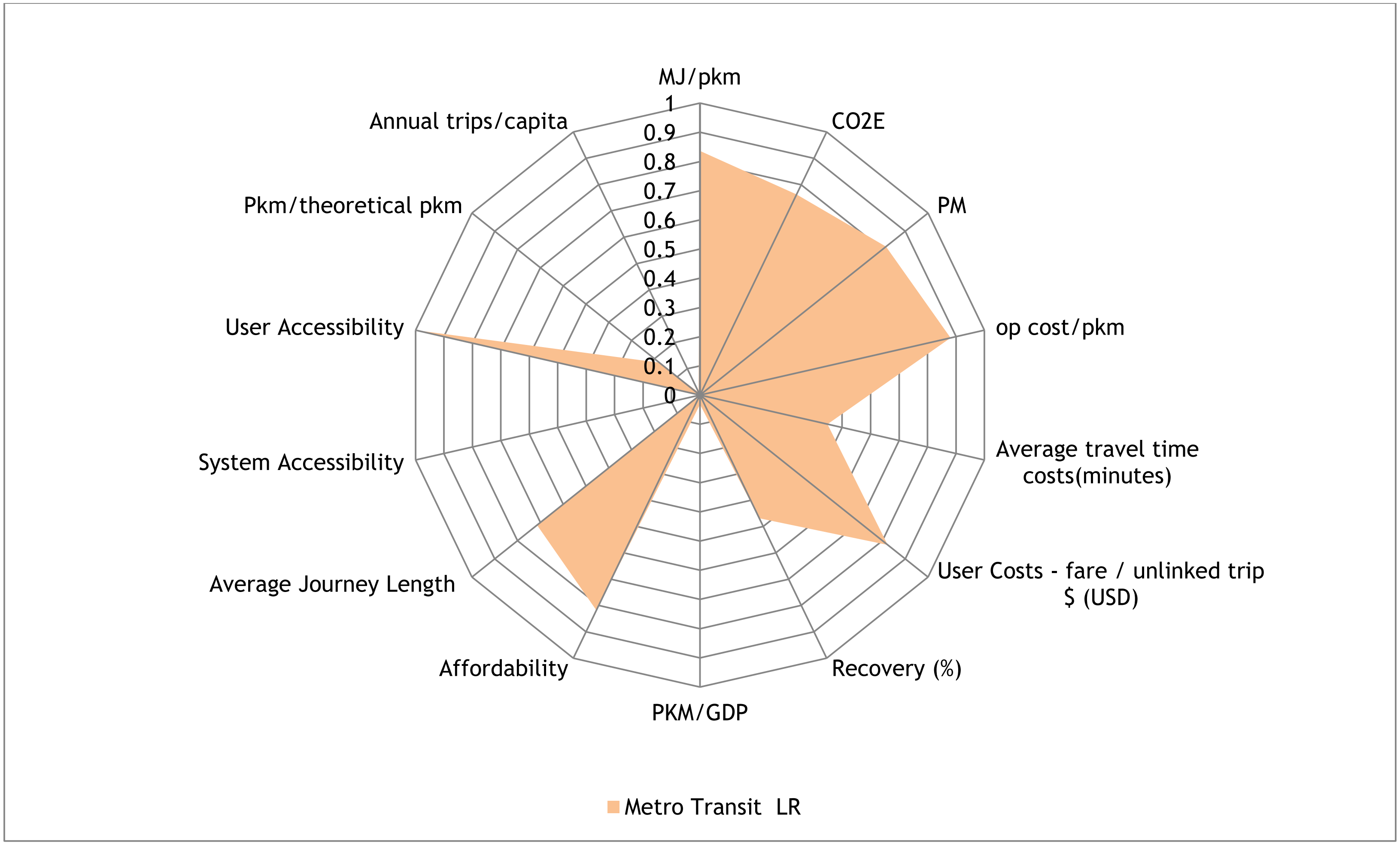
San Francisco Bay Area Rapid Transit District HR


MJ/pkm
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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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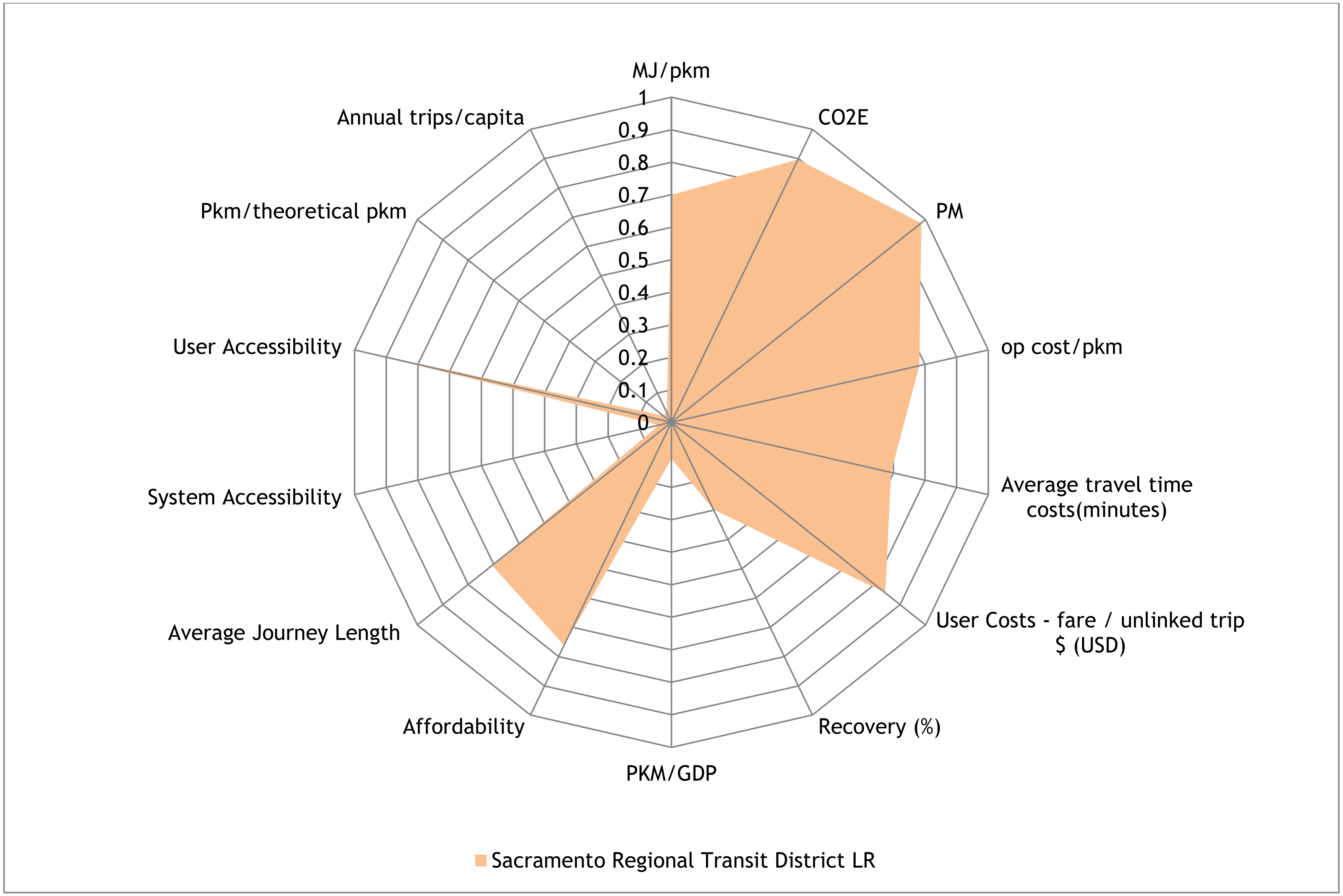
Metro Transit LR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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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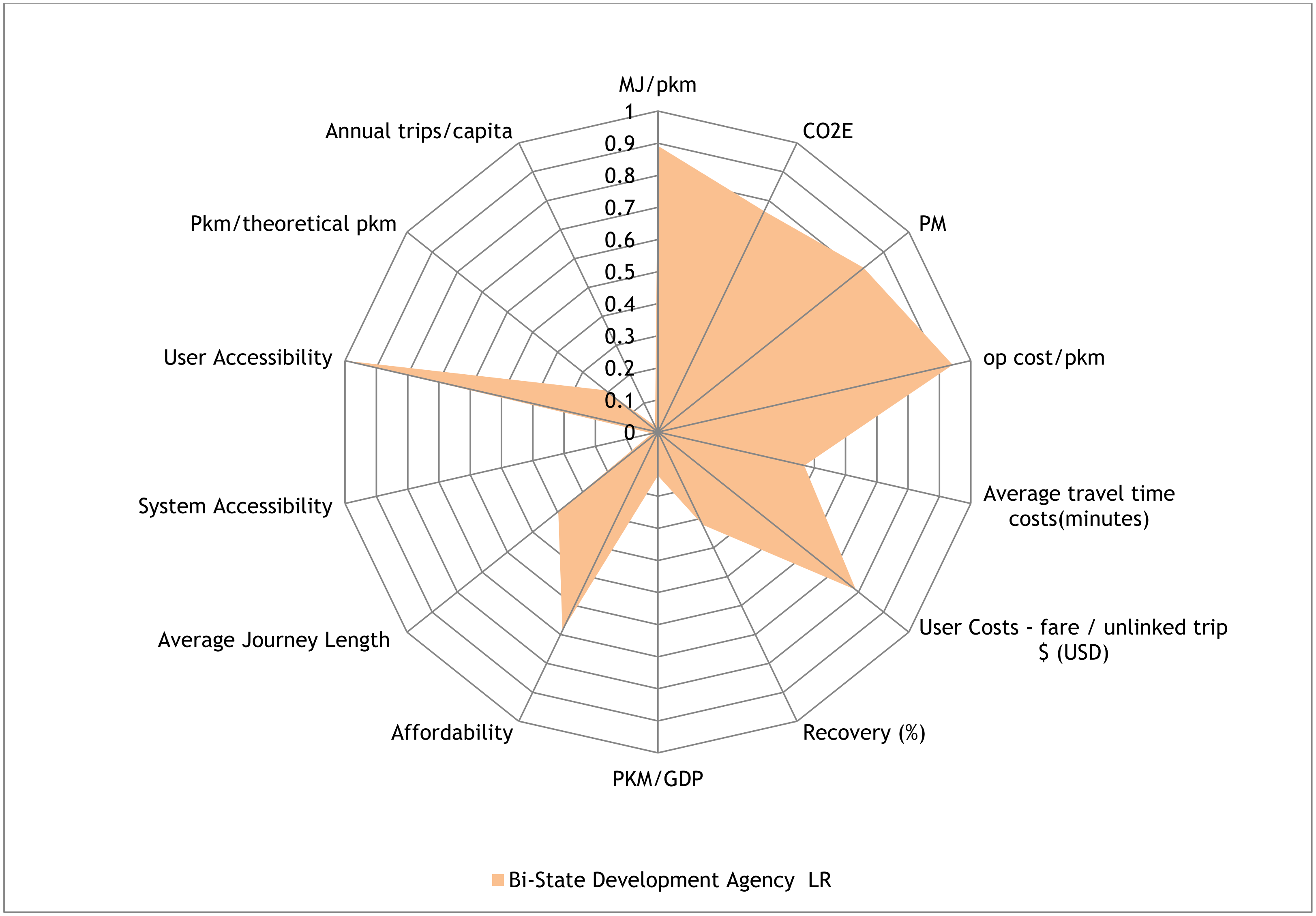
Sacramento Regional Transit District LR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Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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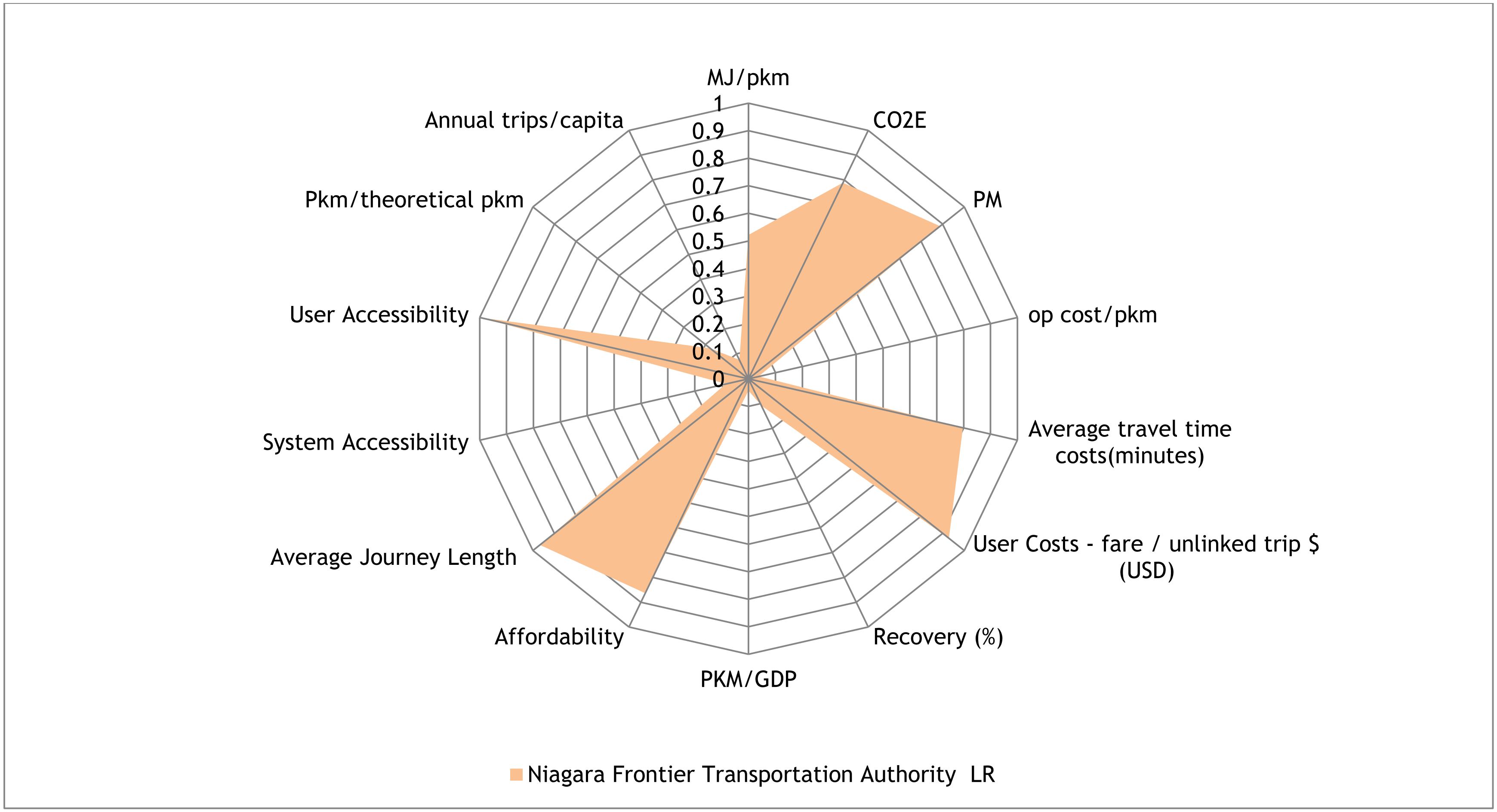
Bi-State Development Agency LR



MJ/pkm
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Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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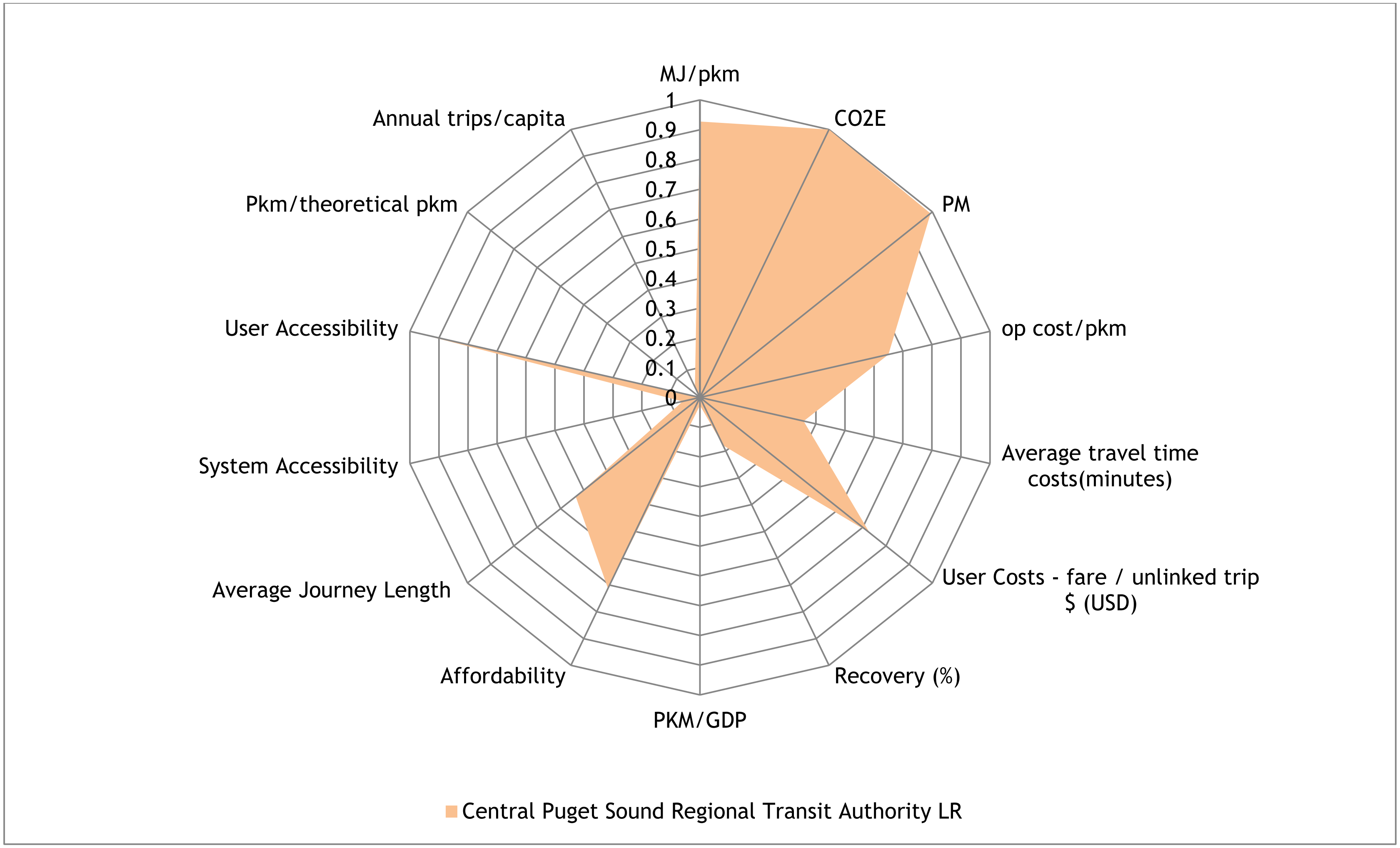
Niagara Frontier Transportation Authority LR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Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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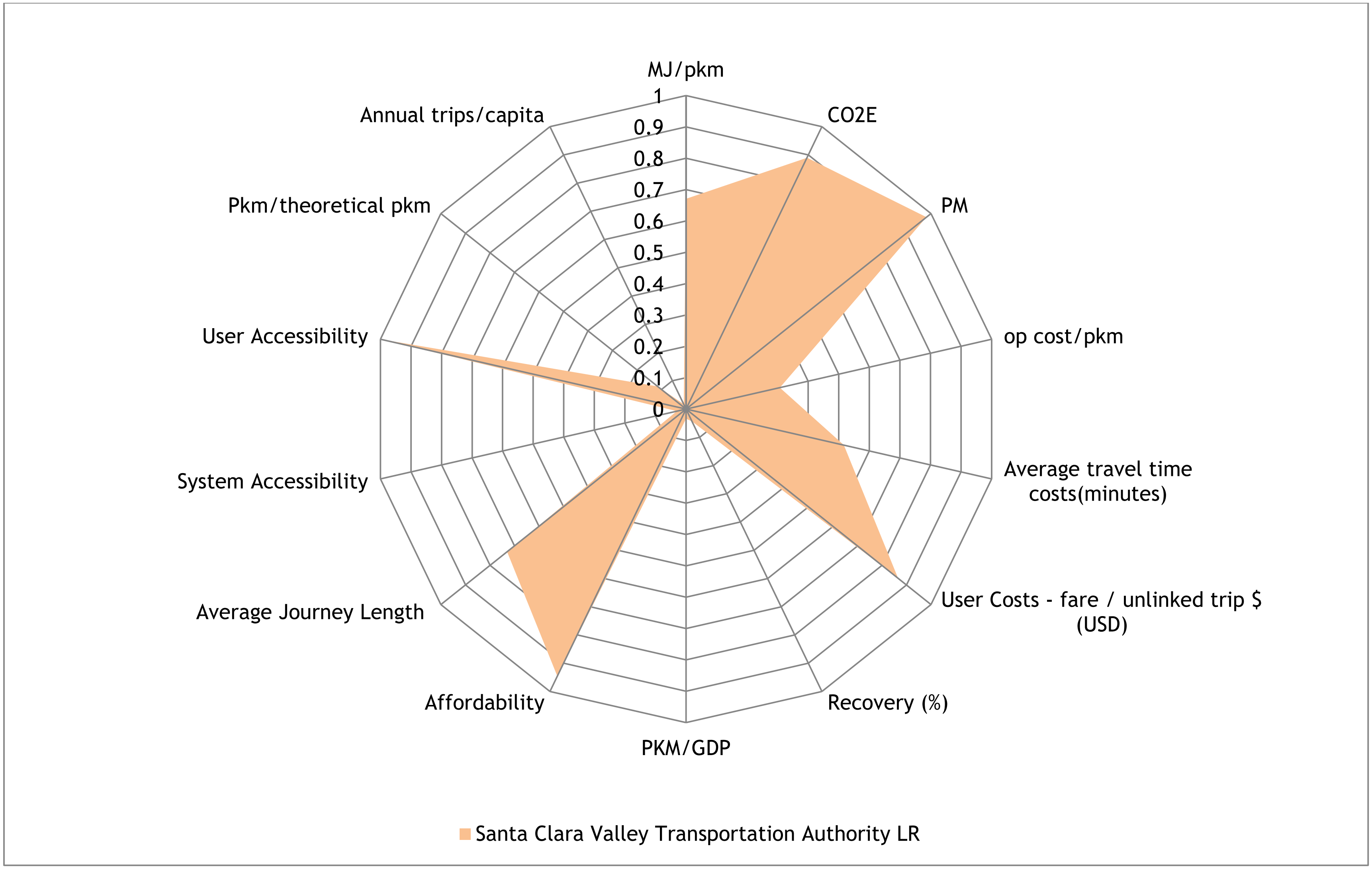
Central Puget Sound Regional Transit Authority LR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Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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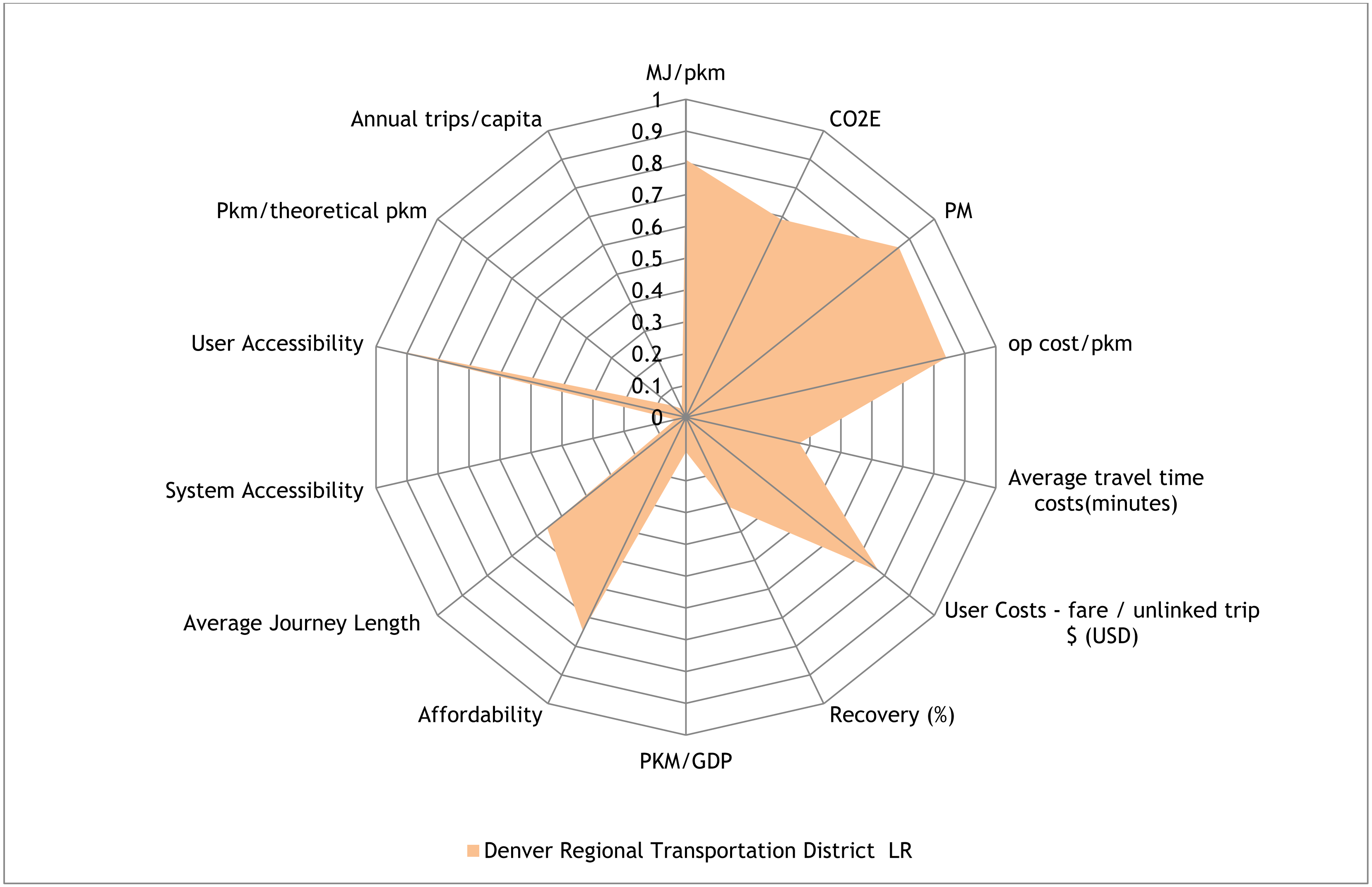
Santa Clara Valley Transportation Authority LR


MJ/pkm
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Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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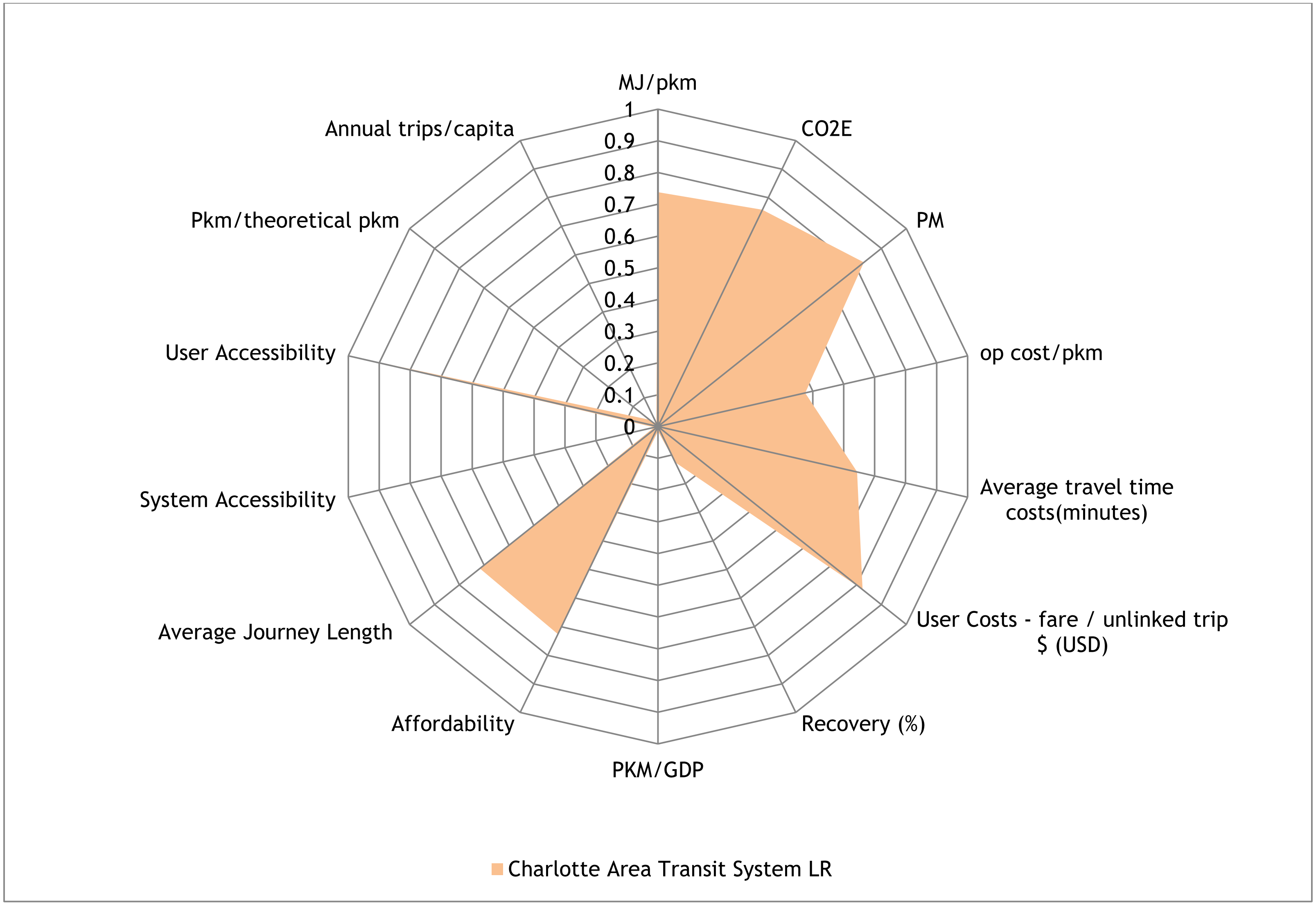
Denver Regional Transportation District LR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Average Journey Length
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User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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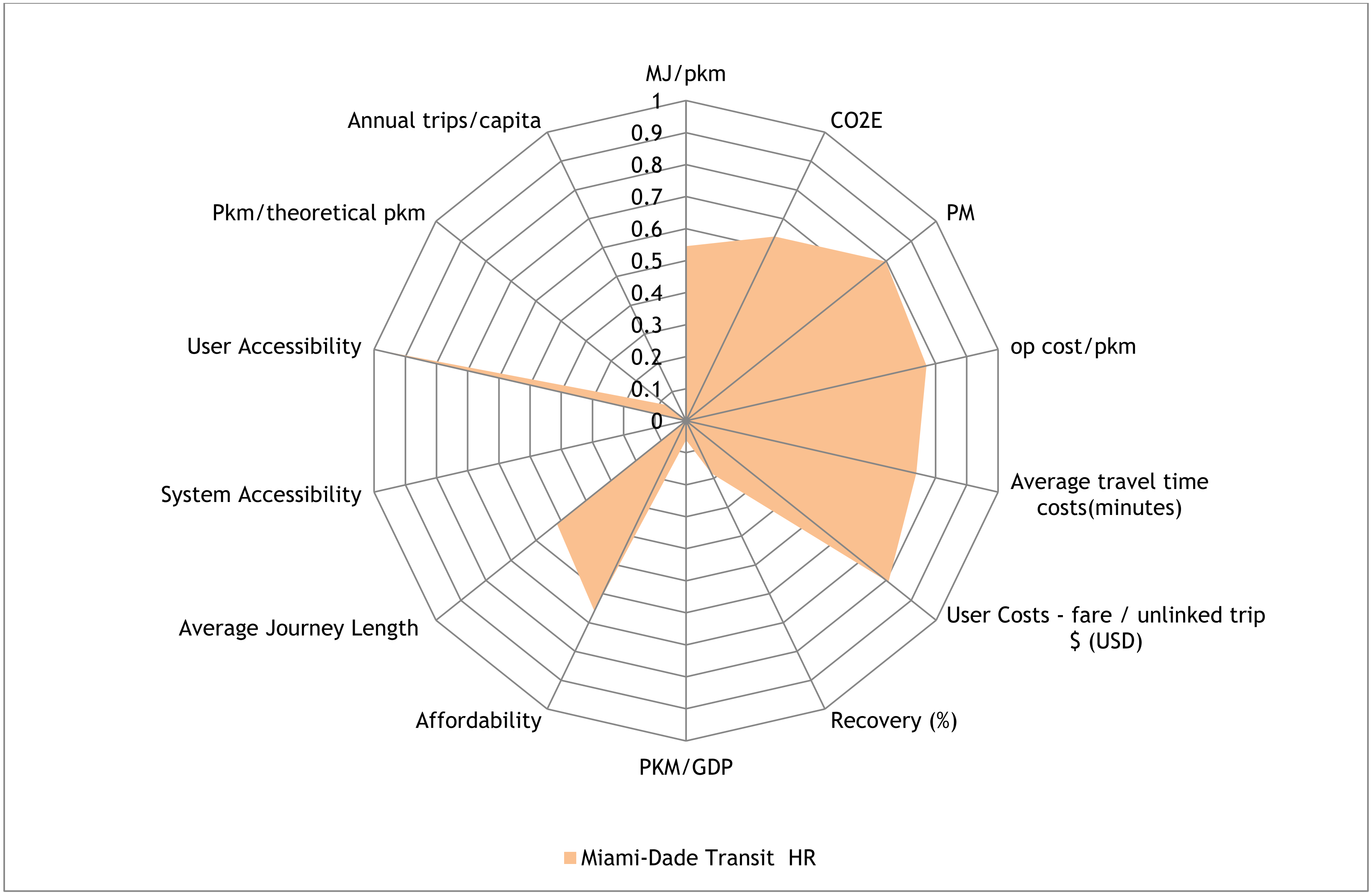
Charlotte Area Transit System LR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Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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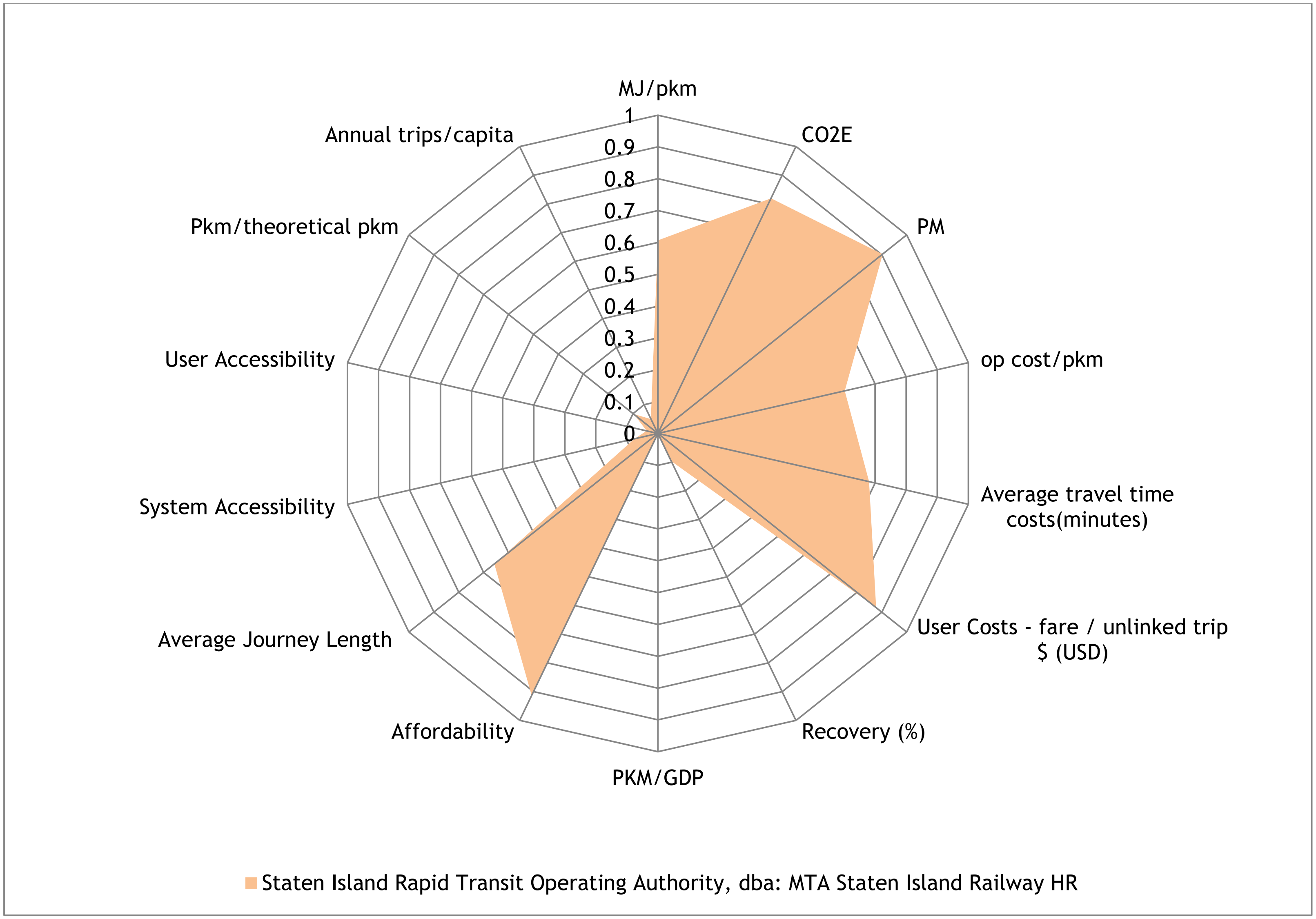
Miami-Dade Transit HR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Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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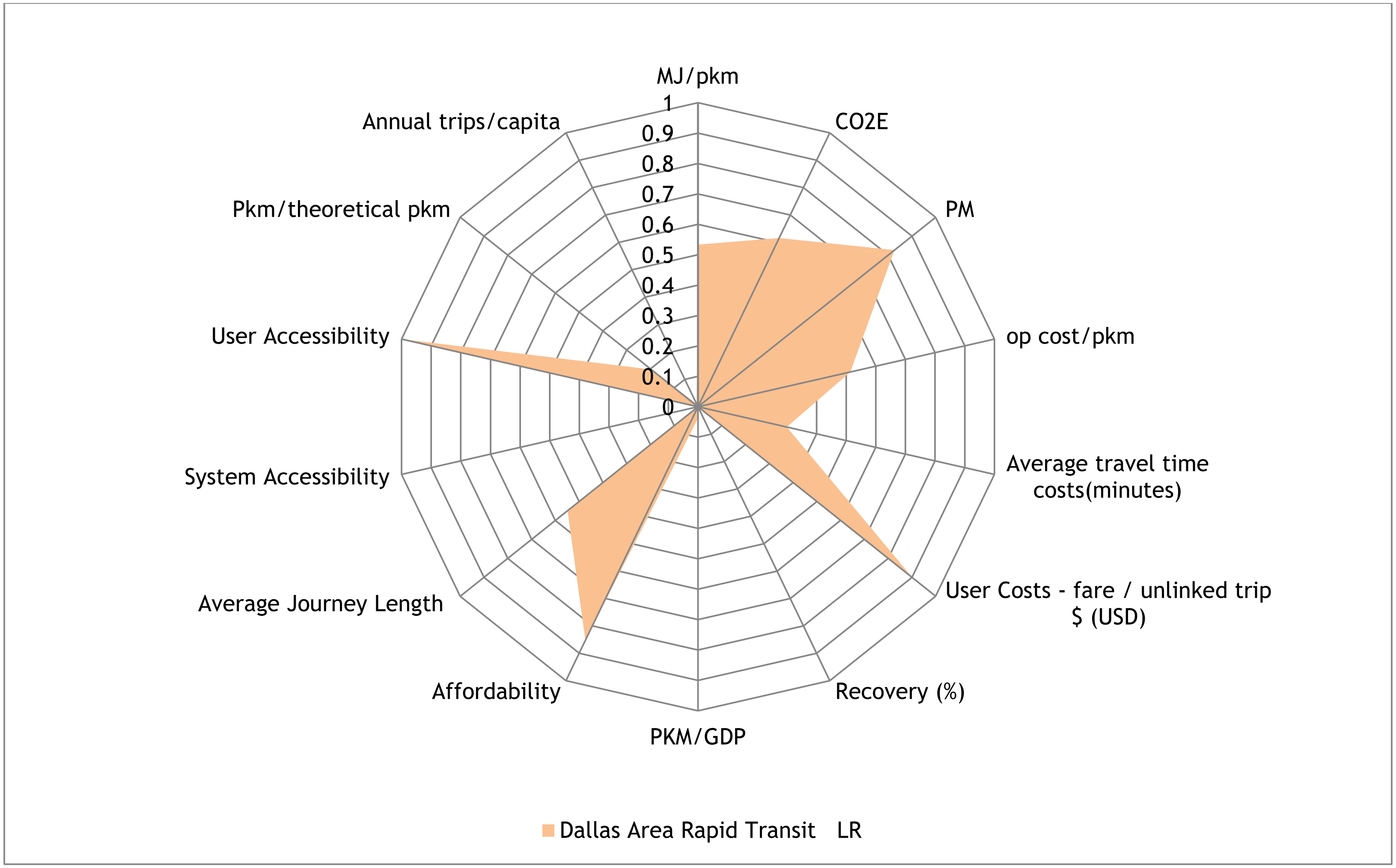
Staten Island Rapid Transit Operating Authority, dba: MTA Staten Island Railway HR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PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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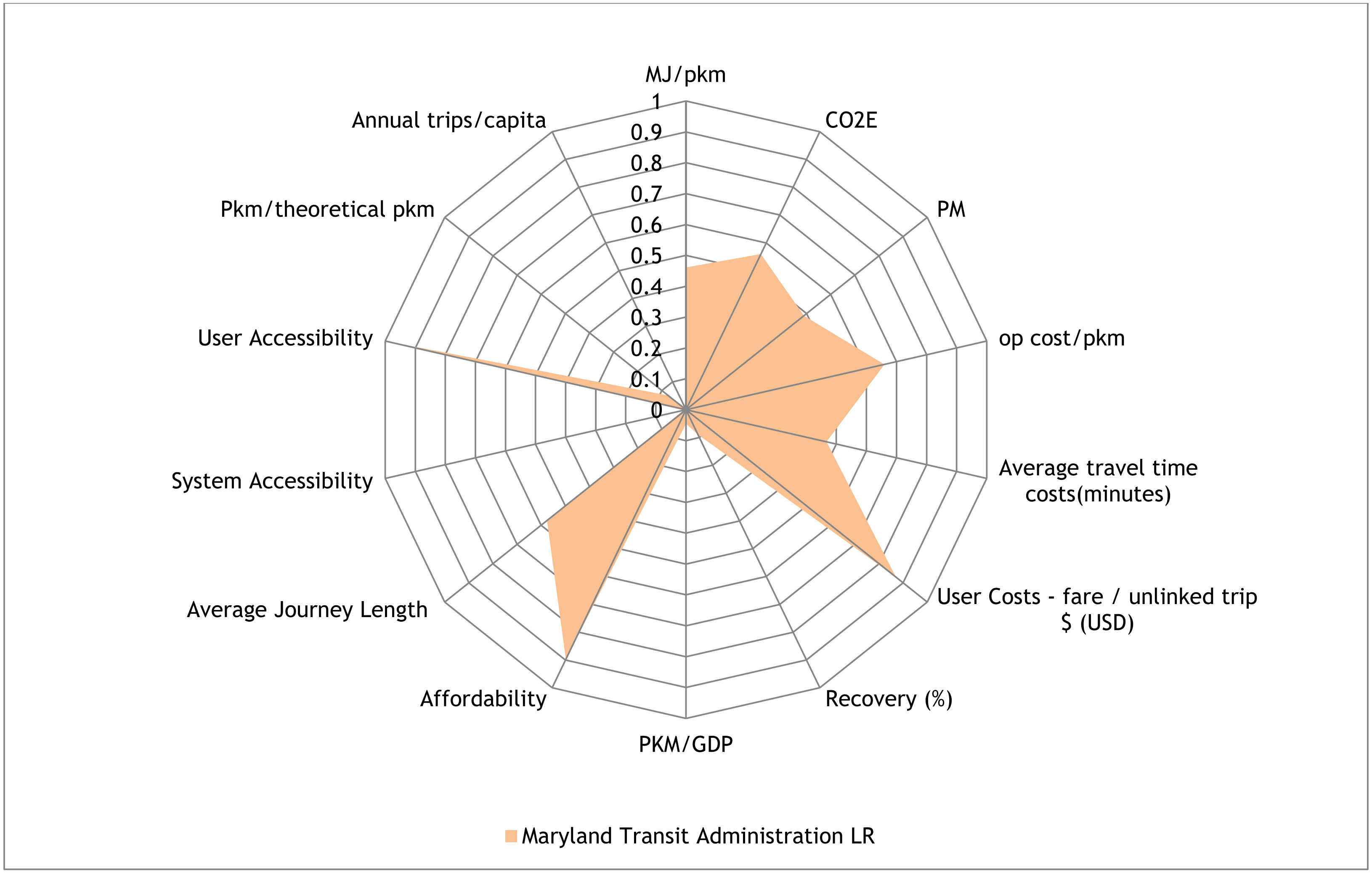
Dallas Area Rapid Transit LR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Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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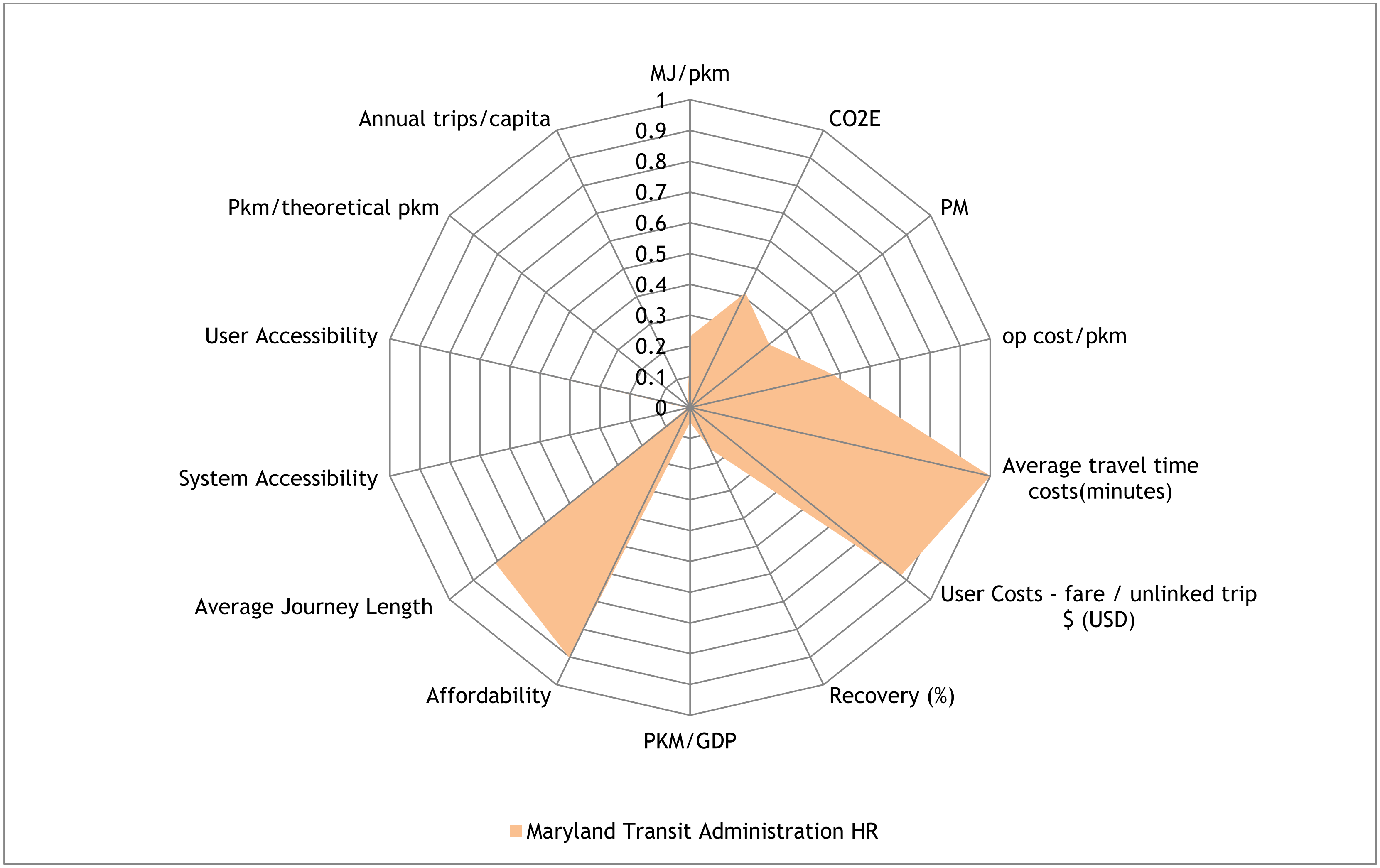
Maryland Transit Administration LR


MJ/pkm
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Average Journey Length
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User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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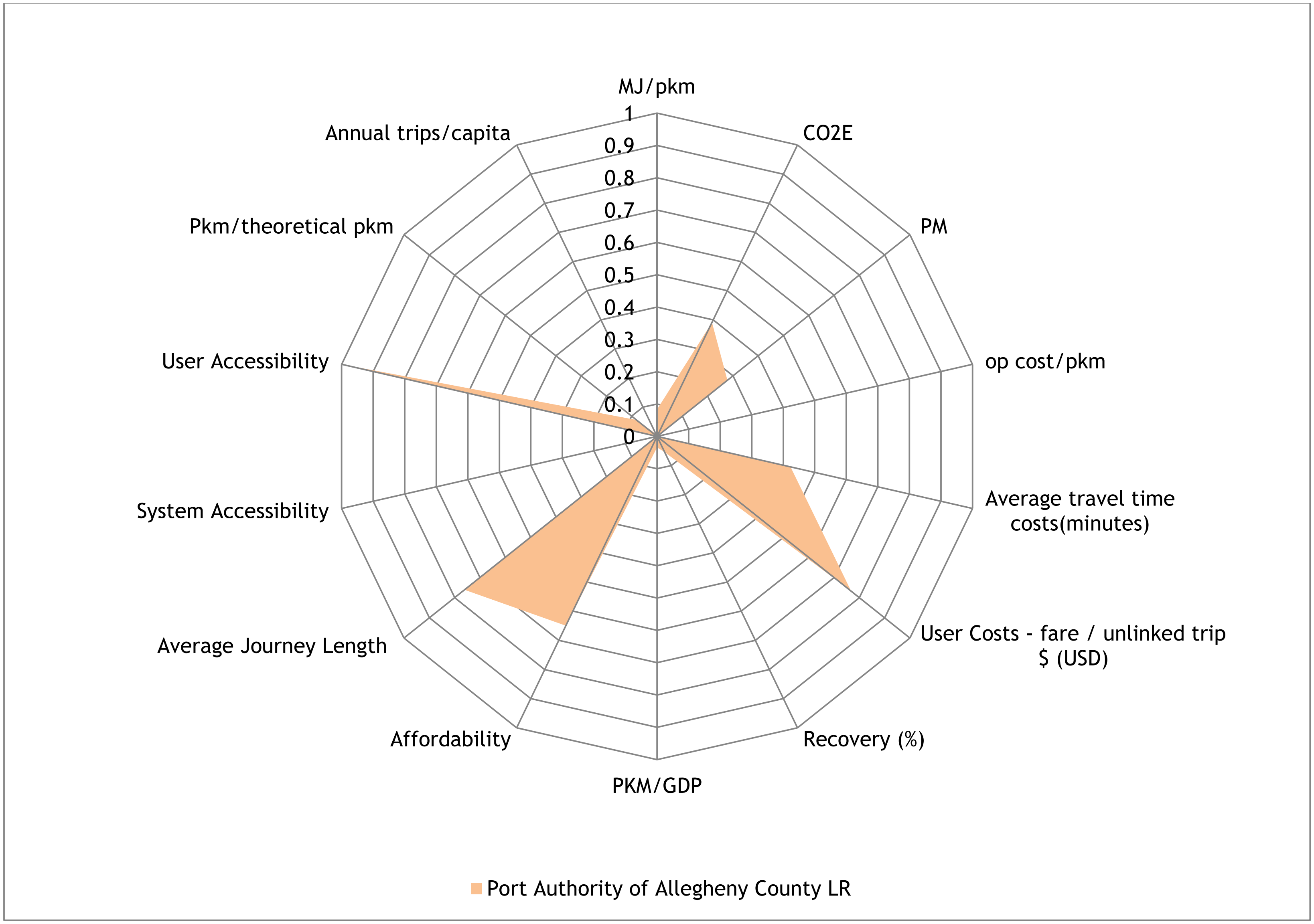
Maryland Transit Administration HR


MJ/pkm
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PM
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User Costs - fare / unlinked trip $ (USD)
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PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
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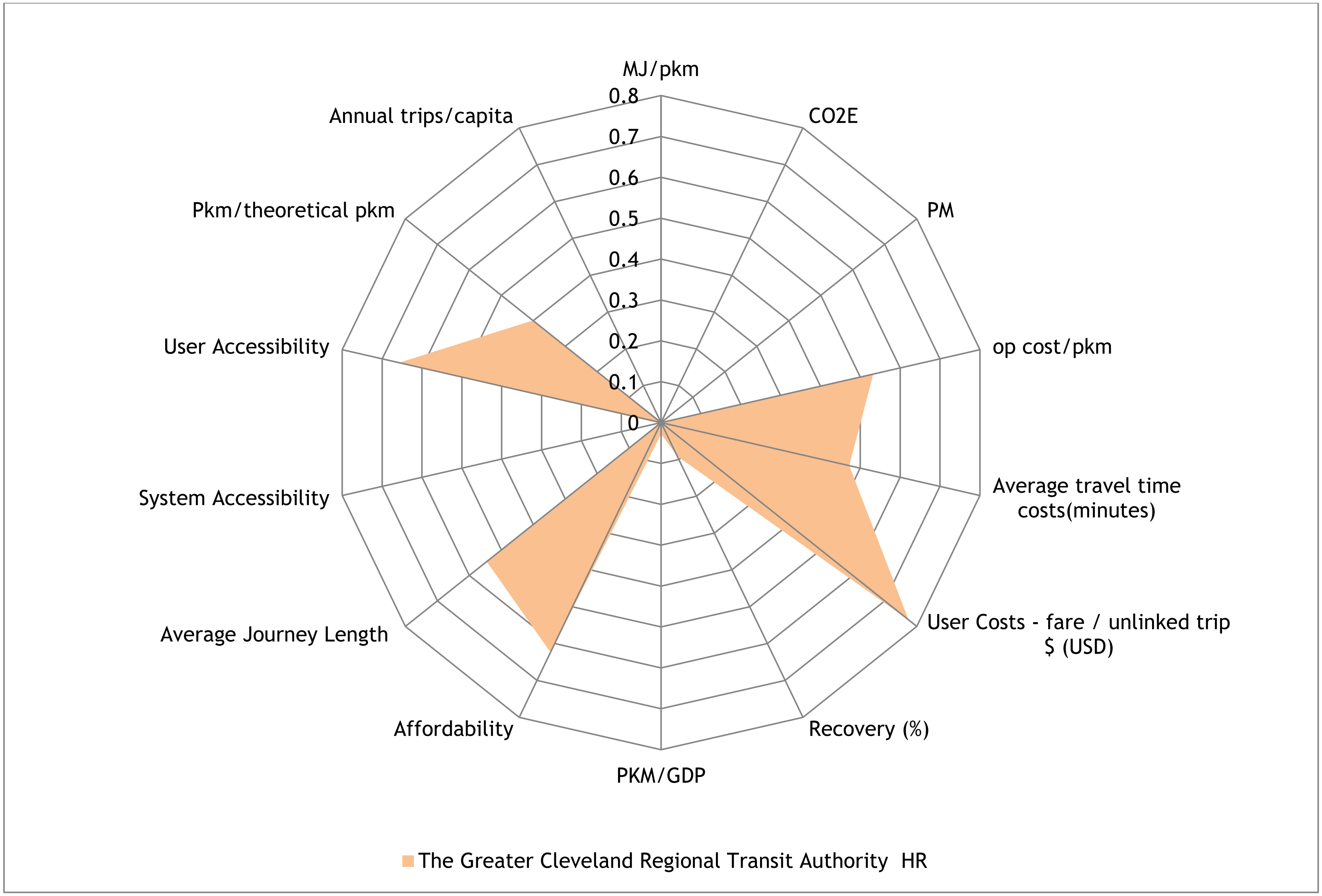
Port Authority of Allegheny County LR


MJ/pkm
CO2E
PM
op cost/pkm
Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
0.8
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0.6
0.5
0.4
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0.2
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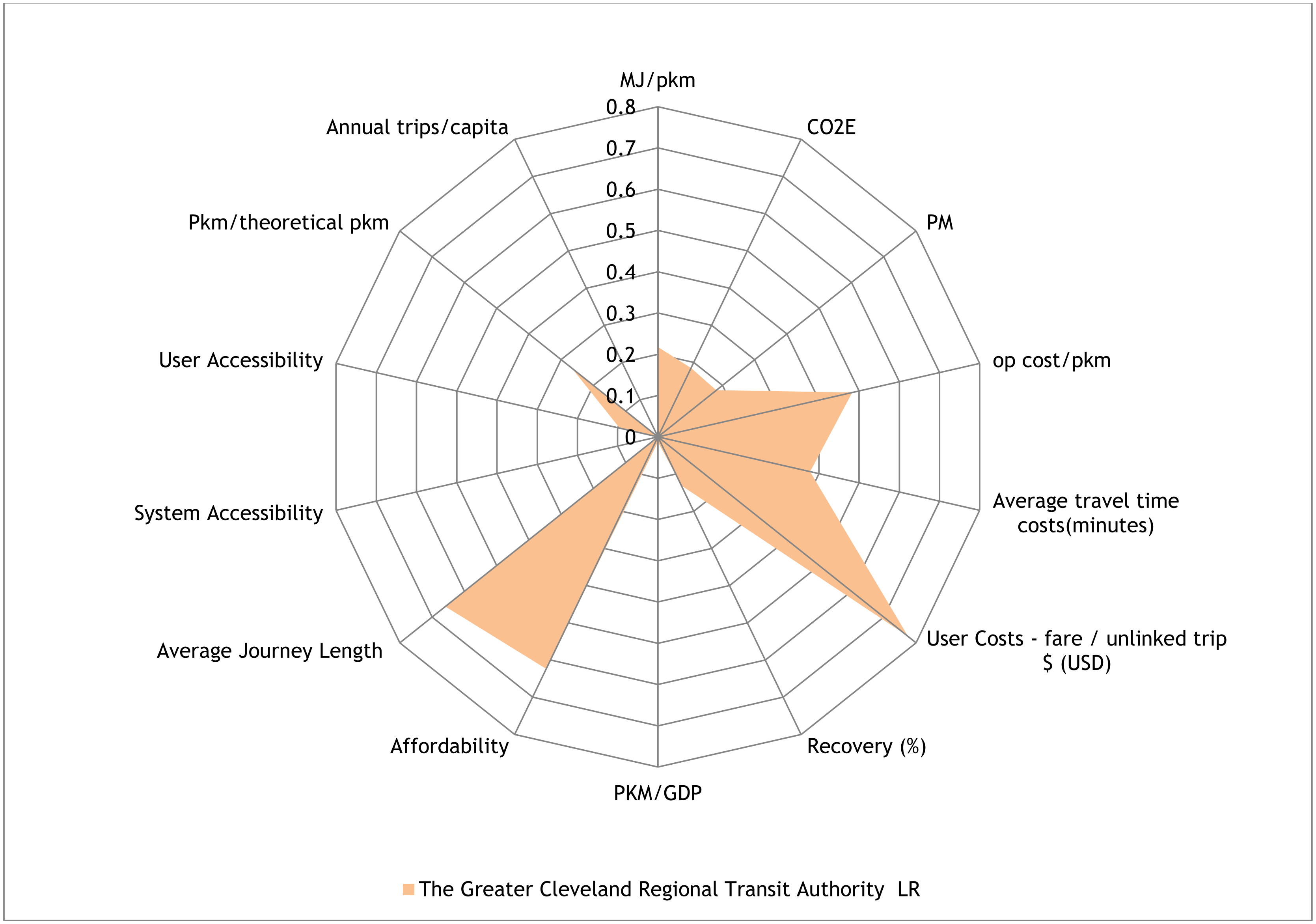
0
The Greater Cleveland Regional Transit Authority HR


MJ/pkm
CO2E
PM
op cost/pkm
Average travel time costs(minutes)
User Costs - fare / unlinked trip $ (USD)
Recovery (%)
PKM/GDP
Affordability
Average Journey Length
System Accessibility
User Accessibility
Pkm/theoretical pkm
Annual trips/capita
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
The Greater Cleveland Regional Transit Authority LR