MULTI-CRITERIA DECISION MAKING WHEN PLANNING SUSTAINABLE MULTIMODAL TRANSPORTATION ROUTES in a LINEAR CORRIDOR

MULTI-CRITERIA DECISION MAKING WHEN PLANNING SUSTAINABLE MULTIMODAL TRANSPORTATION ROUTES IN A CORRIDOR

A Dissertation Presented

by

MARIE P. LOUIS

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ABSTRACT

MULTI-CRITERIA DECISION MAKING WHEN PLANNING SUSTAINABLE MULTIMODAL TRANSPORTATION ROUTES IN A CORRIDOR

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In urban and suburban locations, public transit can be seen as an effective mode of daily transportation. The majority of the time, travelers would seek the cheapest, shortest, and possibly most eco-friendly means of transit. When designing public transit network systems, transportation planners and decision-makers, with input from stakeholders, should strive to optimize transportation services to meet the needs of the population most efficiently and at the lowest cost, that is, providing a transportation system that fits the three E's of the sustainability concept: environment, social equity, and economic.

Previous studies have focused on sustainability as the primary concern in public transportation system design and performance; however, studies attempting to model

environmental impacts in addition to costs did not account for specific characteristics of the transit vehicle's driving cycle (i.e., time spent cruising, idling, accelerating, and decelerating) or evaluated all the E's of sustainability. This dissertation explores the Pareto frontier of the three aspects of sustainability in the design of multi-modal public transportation routes with unequal space between the stops and stations with no transfers in a linear corridor by simultaneously accounting for greenhouse gas (GHG) costs, capital, operating and maintenance costs, and users' costs. The proposed models do not account for the spatial structure of the city, but allow for a comparison of emissions and costs between various public transit trunk technologies and the use of private vehicles (i.e., conventional and hybrid) operating along the same corridor assuming static traffic conditions.

The goal of this research is to support the transportation planning process by providing a systematic analysis method to evaluate the trade-offs of public transportation modes vis-*à*-vis the three aspects of sustainability among private vehicles. Additionally, the results of this research aim to assist transit policy-makers and practitioners when solving the multi-criteria problem of minimizing operation and passenger costs as well as the costs of GHGs in terms of CO_2-equivalent. To achieve these objectives, analytical models are developed for user cost (a measure of social sustainability), agency cost (a measure of economic sustainability), and GHG emissions (a measure of environmental sustainability). Each of these components is monetized and combined into a single generalized cost function, which is minimized by optimizing stop spacing and service headway along the route.

The findings indicate that a dedicated bus lane (DBL) is the most sustainable technology that can meet all three E's of sustainability up to an approximate level of demands of 200 trips per pour per mile compared to the other technologies. When the level of demand is higher than 200 trips per mile per hour, the full bus rapid transit appears to be the most sustainable mode. However, when the level of demand

is within the range of 0-3.99 trips per mile per hour, hybrid vehicles are competitive with a dedicated bus lane and the full bus rapid transit (Full BRT) with trade-offs among the other trunk technologies that are investigating in this dissertation. Light rail transit is found to be the most environmentally friendly among all transportation modes or technologies in this dissertation. Furthermore, a mixed traffic (MT) bus is found to be the most eco-friendly trunk transit technology compared to the tram. Both light rail and tram are competitive in terms of headways with the DBL for a certain range of demands along the route. The findings also reveal that the cost of GHG emissions is always the smallest portion of the overall cost of service with this proposed methodology for all studied trunk technologies and the variation of the GHG emissions market value does not affect the decision making when selecting the most sustainable transportation mode(s) for a city. The main takeaway of the research in terms of sustainability is that a full BRT is not always the most sustainable technology for a city, because a DBL has the potential to simultaneously meet all three E's of sustainability at certain level of demands. When the rails' electricity comes from a nuclear offshore power-plant, metro heavy rail (MHR), tram, and light rail transit (LRT) were found to be the most eco-friendly,with MHR resulting to the highest and LRT to the lowest emissions.

The units that will be used in this study are dollars per passenger or hour, miles, and metric ton of CO_2e.

Keywords: Sustainability, Vehicle Specific Power (VSP), Light Rail Transit (LRT), Full Bus Rapid Transit (BRT), Metro Heavy Rail (MHR), Multimodal Decision Making, GHG Emissions Cost, Dedicated Bus Lane

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF ACRONYMS AND ABBREVIATIONS

ABC	Artificial bee colony
AEA	Auto Gas emissions analyzer
APTA	American Public Transportation Association
AVG	Average
BLIP	Bus lane with intermittent priority
BRT	Bus rapid transit
CFC	Chlorofluorocarbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DBL	Dedicated Bus Lane
DOT	Department of Transportation
EPA	Environmental Protection Agency
FFS	Free-flow speed
FHWA	Federal Highway Administration
FS	Peak fleet size
FTA	Federal Transit Administration
GC	Generalized cost
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic information system
GWP	Global warming potential
HC	Hydrocarbon
HCFC	Hydro chlorofluorocarbon
HEV	Hybrid electric vehicle
HRT	Heavy Rail Transit
IBL	Intermittent bus lane
ITDP	Institute for Transportation Development and Policy
ITS	Intelligent transportation system
KE	Kinetic energy
LB	Local bus
LCB	Logistics function cost
LRT	Light rail transit
MCDM	Multi-criteria decision making
MHR	Metro heavy rail
MT	Mixed Traffic

NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NTD	National Transit Database
OECD	Organization for Economic Co-operation and Development
PC	Passenger car
PMT	Passenger mile traveled
PRS	Parks and recreation setting
PT	Public transportation or public transit
PTSP	Public transit signal priority
RNDP	Road network design problem
ROW	Right-of-way
SCC	Social cost of carbon
SD	Sustainable development
TCRP	Transit Cooperative Research Program
TDP	Transit development plan
TNDP	Transit network design problem
TOD	Transit-oriented development
TSP	Transit signal priority
U.S.DOT	United States Department of Transportation
U.S.EIA	United States Energy Information Administration
USEPA	United States Environmental Protection Agency
VD	Vehicle-distance
VHT	Vehicle-hours traveled
VMT	Vehicle miles traveled
VOC	Volatile organic compound
VSP	Vehicle specific power
VTPI	Victoria Transport Policy Institute
WMATA	Washington Metropolitan Area Transit Authority

EXECUTIVE SUMMARY

For the last decade, research studies have focused on the positive impacts of public transit and alternative modes of transportation such as reduction of traffic congestion and associated reduction in travel time. Reduced travel time initiates a cascade of positive environmental and health benefits: mitigation of adverse health conditions, such as asthma, which are aggravated by air pollution; reduction of emissions, which are the primary component of greenhouse gases (GHGs) creation of local jobs (Woodcock et al., 2009; Litman, 2003; Van Vugt et al., 1996); and improved accessibility to goods and services (Gazel and Schwer, 1997; Ong and Blumenberg, 1998; Cervero and Duncan, 2002).

Mowen et al. (2008) reviewed several studies to investigate the benefits and relationships of transportation and zoning variables vis-*à*-vis parks and recreation settings (PRSs) and intensities of physical activity (PA). Moving toward the goal of sustainability, should jurisdictions focus on investing in projects that concurrently take into account the three E's of sustainability? If so, what tools and data are needed by government and private entities to make rational decisions accounting for trade-offs in the three aspects of sustainability?

Contemporary studies in the public transportation sector focus on designing transit network systems; however, those studies are weighted toward user costs and operations. This study, too, compares regular buses (e.g., mixed traffic (MT) and dedicated bus lanes (DBL)), full bus rapid transit (BRT), tram, light rail transit (LRT), and metro heavy rail (MHR), but with the main objective of appraising cost effectiveness while concurrently basing decision making on the three aspects of sustainability accounting for the driving cycle components of implementing BRT, LRT, MHR, and

local and feeder buses, taking into account the spatial structure of the city. For the purpose of this study, cost effectiveness includes capital, operations, maintenance, access time, waiting time, transfer time (e.g., zero), in-vehicle time, and GHG emissions costs in comparison to the private vehicles operating in the same linear corridor. This study also focuses on static traffic conditions. Under static traffic conditions, the road remains uncongested and the vehicles are most likely operating with free flow speed. The purpose of the analytical models is to arrive at a logistics function cost (LFC) to plan and design the most economical, equitable, and eco-friendly multi-modal transportation network routes or systems in a linear corridor that can be modified to fit any city.

A strategic mathematical model for each trunk technology in this study was developed. The main purpose of the finalized overall model/tool is to assist transportation decision makers (DMs), transportation planners and designers, stakeholders, transit agencies, and practitioners DMs in selecting which of the studied transportation modes will be the best fit for a city, based on the three dimensions of sustainability. The final decision-making support tool of this study evaluates a wide range of related parameters, including the following:

- Optimum headway and average distance between stations or stops
- Average trip length
- Structure of the route (e.g., linear, radial/ring, grid, hybrid, etc...)
- Travel demand rate
- Capacity of the bus/train
- Different types of technology used
- Commercial and free-flow speed

- Signal cycle length
- Fuel and propulsion
- Capital, operating, and maintenance costs
- Total length of the route

CHAPTER 1

INTRODUCTION

This chapter presents a summary of the problem as well the three aspects of the sustainability concept that this study is based on to evaluate multimodal transportation. This chapter introduces a connection between the studied public transportation (PT) modes in this research and the sustainability concept. The chapter provides a brief history of each mode that will be investigated in this study. The sustainability concept is also explained in this chapter to elaborate on why the adaptation of the studied public transportation modes is important to any country worldwide.

1.1 Background

Automobile traffic congestion affects the lives of individuals in developing and developed countries. A study by (Michelle Ernst and Greene-Roesel, 2003) found that, in the United States, more than 50% of carbon monoxide (CO), 34% of nitrogen dioxide (NO_2), 29% of hydrocarbon emissions, and as much as 10% of fine particulate matter emissions are attributable to motorized traffic on a national scale. In 1999, the United States Environmental Protection Agency stated that in the U.S., approximately two-thirds of all CO and about one-third of NO_2 emissions, as well as volatile organic compounds (VOCs), are attributable to transportation sources (USEPA, 2002).

Furthermore, according to the U.S. Energy Information Administration, in 2015, the public transportation sector emitted approximately 18 million metric tons of carbon dioxide (CO_2) in 2014 (US EIA, 2015). Currie and Walker (2011) also found

that traffic congestion reductions after the implementation of E-ZPass or electronic toll collection on highways reduced the rate of prematurity and low birth weight among mothers who are within 2km of a toll plaza between 6.7%, 9.1% and 8.5%, 11.3% respectively. Currie (2009) found that low birth weight has been linked to future health problems and lower educational attainment.

Some transportation experts view traffic congestion as an infrastructure issue, while others view it as a management-related problem. Because of those differing viewpoints, some countries are proposing to resolve the issue of traffic congestion by building more roads, but this strategy sometimes exacerbates the dilemma and introduces the demand for parking space, since land use is interconnected with transportation, as demonstrated by Braess's paradox (Mitchell and Rapkin, 1954; Kelly, 1994; Moore and Thorsnes, 1994; Kienitz, 1999; Handy, 2005; Litman and Burwell, 2006).

One potential solution to traffic congestion is extensive use of public transit and other alternative modes of transportation. Travelers would be encouraged to park their personal vehicles at the closest station or walk to the bus stop, and then ride public transit. This shift to public transportation would contribute to reduced traffic congestion and, therefore, emission reduction. Feeder or regular buses, bus rapid transit (BRT), and light rail transit (LRT) are an advancement of public transit to influence human beings to use public transportation in an efficient way.

Feeder and local buses; mixed traffic; light rail, lite, standard, and full bus rapid transit; and metro heavy rail (MHR) systems have been investigated by transportation researchers over the last decades. Feeder bus routes can be defined as buses that provide a means to transport travelers from the local bus stop to the rapid transit/train stations or express-bus terminals/stations. Feeder buses can also serve as "regular or local" buses, as the main difference among these buses is the headway (time or distance between buses). Local and feeder buses are recognized as a

mode of transportation that can effectively help balance the modal split, connecting passengers to rail, heavy metro, express buses, or bus rapid transit stations, which can enhance public transportation accessibility. A number of studies have analyzed feeder buses from the standpoint of cost effectiveness (Byrne and Vuchic, 1972; Hurdle, 1973), optimal bus route network (Bansal, 1981; Lesley, 1976), as feeder bus network-design problems (FBNDP) (Kuah and Perl, 1989; Sivakumaran et al., 2012), and bus route planning (Silman et al., 1974). Verma and Dhingra (2005) have investigated optimal feeder bus routes to help provide effective and efficient connection to existing or current rail-based systems for a city. Some studies have used different heuristic methods (Lampkin and Saalmans, 1967; Mandl, 1980; Dubois et al., 1979; Dhingra, 1980) and other studies have focused on the integrated planning framework aspects, where one or more feeder buses are considered to provide better accessibility to multi-modal corridors (Chien and Schonfeld, 1998; Shrivastava and Dhingra, 2001; Chien et al., 2001).

Among the cities that have successfully operated bus rapid transit, which is defined in this research as dedicated busways with their own rights-of-way (ROW), the majority show that bus rapid transit has had great influence on the environment in regards to spreading less greenhouse gas emissions in the air improving air quality (Vincent and Jerram, 2006; Satiennam et al., 2006; Harnack, 2007; Wöhrnschimmel et al., 2006; Hughes, 2012). The development of BRT systems was limited to the Americas in the 1970s (Levinson et al. (2002) Ernst (2005), and Wright (2002)). The first-ever broad development of BRT was launched in 1974 in Curitiba, Brazil, although there were some small bus rapid transit projects prior to that year. The successful implementation of BRT in Curitiba inspired a variety of other cities to develop similar bus rapid transit system projects. BRT systems were introduced in Quito, Ecuador (1996), Los Angeles, USA (1999), and Bogotá, Columbia (2000). After the TransMilenio project in Bogot started operation in 2000, the attention of the

world community was drawn to BRT systems, and their development burgeoned. In a recent study, the Institute for Transportation Development and Policy (ITDP) reported that by the end of 2014, there were approximately 666 BRT systems around the world, with 99 in Brazil, 334 in China, 152 in Mexico, and 81 in the United States. These include what some authorities refer to as express buses. In express buses, the fare is paid as soon as the rider comes onboard, whereas in BRT, it can be paid at boarding or deboarding. Express buses and BRT are both important, but a BRT provides more features (e.g, real-time travel information, advanced buses, off-board fare collection, platform level boarding, etc...) than the express bus.

Street cars as a mode of public transportation started in Germany before World War II. After the war, the Germans transformed streetcar networks into a model light rail transit system (LRT). The first light rail system in North America began operation in 1978 when Edmonton, Alberta, espoused the German Siemens-Duewag U2 systems. LRT includes the streetcar, or trolley car, and it is defined by the American Public Transportation Association (APTA) as an electric rail that has a light-volume traffic capacity compared to heavy rail. LRT uses a shared or exclusive right-of-way with high or low platform loading and multi- or single-car trains. The term light rail was first coined in the 1960s to avoid the U.S. terms trolley or streetcar. LRT has been used on many continents, such as North America, Europe, and Asia, to reduce traffic congestion, reduce pollution, increase property values, foster economic development, and provide a means of transportation for the poor (Garrett, 2004; Dimitriou Harry, 1992). LRT sometimes uses renewable energy such as solar, micro hydro, wind, and coal to generate power for operations.

Passenger rail and urban transit rail can be operated using different types of power supply. Some of their power supplies are dual-mode, diesel electric, all electric, and hybrid electric. LRT has known to be one of the transit modes that is most likely used in worldwide busy urban corridors to facilitate accessibility for passengers between

downtown, campuses, shopping centers, and other places. LRT in many cases is operated using an exclusive ROW, but some systems are operated on a shared right-of-way with vehicular traffic. Most of the time, one LRT contains one to four railcars, which are able to transport up to 220 passengers by traveling at a speed of up to 105 kilometers per hour. Some LRT systems use diesel, but most of the systems use electric multiple units. The electricity might come from different sources, namely coal, solar, and offshore.

Metro systems, also called rail rapid transit, have been internationally defined as subways or heavy rail transit (HRT) (Transit Cooperative Research Program, 1998, Burchell et al. (1998)). Similarly, Wright and Fjellstrom (2003) defined metro systems as urban grade-separated heavy rail metro systems. Compared to light rail transit systems, metro heavy rail consists of electrically propelled trains of cars operating over fully separated ROW. However, metro heavy rail has a higher capacity than light rail transit. Metro heavy rail transit is one of the transit modes that frequently operates with high frequency for urban short-distance trips. Metro heavy rail often operates on exclusive ROW and also has the capability to carry a number of stand or sit passengers. Furthermore, metro heavy rail also operates at a speed less than or equal to 130 kilometers per hour. Similar to light rail transit, metro heavy rail also operates using electric multiple units.

Several factors (e.g., social, economic, and political) can affect transit network system planning and design. Several studies (Turnquist and Bowman, 1980; Van Nes and Bovy, 2000; Fan and Machemehl, 2006; Xie and Levinson, 2007) have focused on city spatial structure/networks as one of the factors impacting overall accessibility, connectivity, and inter-connectivity of public transportation systems. Similarly, this study will also take into account the spatial structure in building the models to generate a sustainable decision-making tool generalized for any city or any public transportation system. Knowledge of a city's structure, the street and infrastructure

layout of the city, as well as location of public and private space, allows planners to place public transit routes with the optimum degree of connectivity and accessibility between residences, school, work, medical facilities, commercial districts, and the like.

The spatial structure of a city allows planners to visualize the whole shape of the city using any geographic tools (e.g., ArcGIS, Google Maps). The latter gives the planners an idea of where residential areas, employers, manufacturers, schools, retail businesses, entertainment, churches, and available land are located and to plan systems with an optimum degree of accessibility and connectivity. Each city has its unique shape and businesses, with neighborhoods integrated either organically or by design; therefore, integrating spatial structure into the planning of transit networks can be beneficial not only to travelers, but also to transportation planners, transit agencies, and decision-makers, by ensuring that transportation systems are aligned with user needs for most efficient use. A range of complementary diverse public transportation modes also has the potential to achieve the sustainable service (e.g., Eco-friendly, equitable, convenient, comfortable, and faster) to the target population. How do stakeholders plan for sustainable transit network systems?

1.2 Problem Statement

Gallivan (2013) states that the transportation sector accounts for nearly 28% of U.S. energy consumption. Buehler and Pucher (2012) reported that the proportion of public transport trips and passenger volumes per capita from 1982 to 2010 in the United States versus all other transportation modes has declined. On the other hand, in Europe, overall passenger volumes and trips via public transportation have increased. The latter analysis excludes pedestrian traffic or bicycle trips. Studies by Cervero (1998); Mees (2009); Newman and Kenworthy (1999); Pucher and Kurth (1995); Vuchic (1999) attribute the higher-level ridership to services in European cities that are superior than those in U.S. cities. Although researchers have tried

to sway public opinion toward the use of public transportation, the public are still buying more private cars. The increase in the number of private automobiles not only increases air pollution and its attendant environmental damage and increases the cost of road infrastructure, but represents an added burden on the consumer in the cost of car insurance. By having more cars on the roads, more land will be needed for parking space, detracting from community character, limiting greenspace, and inhibiting sustainability (Gibbons, 1999).

The unsustainability of car growth projected by Sperling and Gordon (2009) will affect climate by displacing environmentally friendly functions with parking spots; emissions; sourcing of fuels; and disposal of hazardous wastes, such as batteries; therefore, effective transit options should be further investigated. This research seeks to identify ways to measure the Pareto frontier between transit modes per route and private vehicles in a linear transit network corridor design.

Researchers in the transportation and environmental sectors, decision-makers, and planners attempt to derive answers to questions such as the following: How can cities be guided in choosing whether to implement sustainable transit mode(s) or suggest adaptation of other energy source alternatives in terms of cost effectiveness, environmental friendliness, and equitability? This and other questions are pertinent in the quest to modernize and popularize public transportation and curb air pollution.

The purpose of this research is to develop a decision tool framework while concurrently quantify all three aspects of sustainability. In addition, this research put together several pieces that were missing from previous related studies to design sustainable multi-modal transportation while accounting for the different real-world driving cycle components. Considering the effects of the different driving cycle components assist not only in getting realistic operations but also in evaluating the vehicle and the human behavior within each cycle of operations during a certain time period. In other words, accounting for all operation modes can assist in capturing all relevant

aspects for vehicle design and operations as well human driving behavior impacts on greenhouse gas pollutants. A mathematical model for each aspect of the sustainability concept, namely, economic, equity, and environment were developed considering multiple metrics, dollars, hour, and gCO_2-equivalent, respectively. All three cost were converted into one unit, namely dollars to add up to one generalized cost function for each mode: local bus/mixed traffic, DBL, full BRT, LRT, tram, and metro routes operating in a linear corridor with homogeneous passenger demand distribution in a small and large cities in any country. In this research a many-to-many travel pattern is investigated where each mode moves through either one or two stops or terminals along the route on its way from its origin to its destination.

The findings of this research are intended to be useful to public transportation decision-makers and to give the populace some criteria to compare the impacts of the three E's of sustainability on MT and dedicated lane buses, LRT, full BRT, tram, and MHR lines in terms of utility while taking into consideration cost effectiveness, user travel time costs, transit demand, and headway or frequency.

1.3 Research Objectives

This research seeks to develop three analytical cost models for the public transit modes and for private vehicles (e.g., conventional and hybrid) using primarily quantitative and computational tools but also drawing from qualitative criteria for investigating the most effective option(s) based on the three aspects of sustainability. This study explores the Pareto frontier of the sustainable aspects when planning and designing full bus rapid transit, light rail transit, tram, metro heavy rail, dedicated bus lane and local bus/mixed traffic routes in a linear corridor with private vehicles for a city. This research seeks to provide new and unique insights about how to sustainably compare and choose among all studied transportation modes for any city. The objective of this research is not to replace the transportation planning

process when choosing any transit mode or to discern the best transit mode. Rather, the intent is to complement the conventional decision process and present comparisons between full bus rapid transit, light rail transit, metro heavy rail, and local or feeder bus routes vis-*à*-vis the three E's of the sustainability concept. The results of this research should ultimately offer transit planners optimized decision tools to apply toward implementation of these transit systems or identification of incentives to travelers to adopting private low-emission vehicles.

1.3.1 Research Questions

The final decision support tool of general cost models will be a sustainable cost model/tool that can be modified to help stakeholders make decisions when choosing among the studied public transportation modes or low emission automobiles. The objectives of this study can be summarized by the following questions:

Aim 1: How shall decision-making models be designed to allow consistent comparison of operations across private vehicles, and transit trunk technology?

Aim 2: At what levels of demand do various transit modes or private cars minimize the three aspects of sustainability: Greenhouse gases (GHG) emissions cost, agency cost, and user cost with the assumption of a specific user's value of time, and GHG emissions market price?

Aim 3: How much does it cost to further reduce emissions by switching travelers from the mode with the lowest generalized cost to the mode with the lowest GHG emission identified in Aim 2?

Aim 4: How does accounting simultaneously for sustainability, in addition to the different components of the driving cycle, affect the findings of public transportation network design, as compared with previous studies?

1.3.2 Motivation

The use of public transportation is increasing, albeit ever so slowly, in cities of various sizes, including Curitiba, Brazil; London, United Kingdom; Bern, Switzerland; Athens, Greece; and Zurich, Switzerland (Zegras and Litman, 1997). Public transportation has been found to offer positive attributes for improving citizens' lives, although a few negative aspects have also been identified, such as long travel times and limited access to destinations not served by transit. Therefore, taking into account the real world-driving cycle and all aspects of the sustainability concept within the design phase can have positive impacts on the users, the environment, transportation policy makers, and transportation practitioners.

1.3.3 Hypothesis

Previous research based on the whole-system evaluations of bus rapid transit,light rail transit, metro heavy rail routes, and buses have variously concluded that one of these modes is more advantageous than the other and is to be preferred as the principal public transportation mode for a city. But that conclusion was reached by working with a specific network structure while ignoring the characteristics of the driving cycle and the three aspects of sustainability. A study of multi-modal transportation design focusing simultaneously on sustainability; and real-life hard data could yield a practical comparison between the costs of sustainability and those found in optimization models.

1.4 Scope and Limitations

This research will analyze the integrated network design of a local bus, full bus rapid transit,light rial transit, tram, and metro heavy rail routes without identifying a specific city. The main reason for the broad scope of this study is to generalize the final decision-making model to be applicable to any city transit system, regardless of

country. Of course, planners and designers would need to adjust the decision-making model to better fit their own cities when planning or designing for the transit routes. One limitation is that the study will explore just one transit network structure when comparing transit mode analysis.

1.5 Research Contribution

The goal of this study is to develop an underlying multi-modal transportation routes decision tool framework which is flexible. This study is unique among previous transit systems studies in that it can analyze existing or planned public transportation routes in multiple cities to assess their potential, rather than studying and comparing the whole system in a specific area. This research will be useful to planners, stakeholders, and decision-makers by providing information critical to choosing transit modes best suited to a set of cities or neighborhoods. The research and information obtained from this research are twofold and will contribute to academic research in the topic areas discussed in the following sections. The academic world, transit agencies, and transit users can benefit from the findings of the study. The contribution of this research can be summarized as follows.

- Provide a framework that can simultaneously evaluate multimodal transportation routes while accounting for all three operation modes of the driving cycle in addition to evaluating multiple sustainability criteria in a holistic and consistent way.
  - Economical
  - Environmentally friendly
  - Equitable
- Provide an approach to modeling GHG emissions of buses and rails, accounting for all operation modes.

- Use a theoretical framework for decision making in the planning phase before collecting considerable data.
- Enable Pareto-optimal frontier analysis of public transit using different fuel sources.

1.6 Organization of the Dissertation

This dissertation is structured into six chapters. Chapter 1 presents a background of the public transportation, sustainability, the aim, contributions, the organization of the dissertation, and all transportation modes that will be studied in this research. Chapter 2 summarizes some of the most related studies that are focused on public transportation, private automobiles, and sustainability to help in identifying and supporting the gaps that this research intends to fill. Chapter 3 describes and explains the methodology used in this research to sustainably plan and design public transit network. Chapter 4 presents the sensitivity analysis Scenarios that are investigated and shows the trade-offs among the three aspects of sustainability between all technologies. Additionally, Chapter 4 presents the discussion and findings obtained from the different case scenarios that were performed in the sensitivity analysis. Chapter 5 provides detailed discussions based on the findings of this research to assist in interpreting the findings in the real world. Chapter 6 presents the conclusions and ideas for future work, with the hope of covering the limitations in this research. This dissertation manuscript also contains two appendices. The tables that summarize the findings among the modes and private vehicles are listed in the appendices; Appendix A contains the findings for trunk technologies and Appendix B contains the findings that relate to private automobiles.

To estimate the values from the breakdown transit trunk technologies tables, each value from the previous studies cited in the comment column was used to forecast the values for year 2016 based on an engineering concept. Some of the values have

to be converted to keep the units in this study consistent. Discount rates for each transit technology were based on the Federal Transit Authority (FTA) as well as real-world public transit systems. Furthermore, the input variable values are listed in the appendices.

1.7 Chapter Summary

Chapter 1 first introduces the GHG emissions question that has attracted the attention of the whole world and how public transportation might be a potential option to assist in meeting the global warming reduction goal if transit stakeholders start including sustainability development in the decision-making process when planning to design a multi-modal transit network. Chapter 1 also details the research objectives and aims that are intended to be solved in this thesis. The contribution of this dissertation, as well as the contributions. The last section of this chapter contains the structure of this thesis to enlighten and assist the readers to straightforwardly navigate through the dissertation thesis. To summarize, Chapter 1 discusses the problem and the need to incorporate sustainability objectives when planning and designing multi-modal transportation.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

The literature review of this research offers an overview of previous studies that have focused on the spatial, structural, sustainability concept, different existing public transportation modes systems, existing public transportation cost models, and other topics. More importantly, this chapter gives a summary of the studies that focused on decision making when choosing among bus rapid transit,light rail transit, metro heavy rail, regular buses, or multi-modal for a city. It also demonstrates the viability of this research and how the findings of this research question could be helpful to stakeholders in different countries and also could impact different aspects of public life. This chapter, therefore, gives insights into the works that have been attempted by other researchers to tackle the sustainable planning and design of bus rapid transit, light rail, metro heavy rail, and feeder bus systems and routes.

2.1 Development of the Sustainability Concept

The concept of sustainable transportation appears to have existed long before it started being applied by researchers. Pedestrian transportation was the first mode of transportation, and it can be termed the most effective for some travelers. With the implementation of technology, such as intelligent transportation system (ITS) and renewable energy, sustainable transportation has evolved as an integral part of urban development and improvement of quality of life. Prior to World War II, passenger tram, rail, and pedal bicycles were the only modes of transportation known in the

western world. Now, however, with the implementation of technology, a number of transportation modes are being placed worldwide to serve the population.

The sustainability concept is a complex concept involving several interpretations based on its interdisciplinary involvement and interconnections (Rodrigue et al., 2013). Being such a complex concept, there are no universally accepted definitions (Beatley, 1995). Litman and Burwell (2006) evaluated the issues in the definition of sustainable transportation. A common agreement of the sustainable concept is related to the (Brundtland et al., 1987), which concluded that the sustainability concept depends up the existence off a sustainable society that favors conditions beneficial for the economic, environmental, and social aspects of a location without compromising the welfare of future generations.

Baptista et al. (2015), in their sustainability report stated that the passenger traffic began in May 1869. The sustainable concept was introduced by (Brundtland et al., 1987). In 2001, the Union Internationale des Transports Publics (UITP), in collaboration with professors Kenworthy and Laube from Murdoch University in Perth, Australia, reported on the concept of sustainable transportation in 100 cities in the Millennium Cities Database (MCD), based on their sustainable transportation performance. The sustainable concept seems to be adopted efficiently in several areas in the world, a finding bolstered by the report published by the New York Times in May, 2013, that Generations X and Y (those born in the 1960s to 1990s) tend to drive less and lean more to public transportation rather than private vehicles.

With the adoption of sustainable transportation, several researchers have focused on responding to important questions, such as how to set improvement goals in this area, how to innovate greener services, and how to educate and engage the population. In addition, several organizations have developed and recommended principles and strategies to reflect fundamental practices and goals for sustainable development (RAE, 2005). Sustainable design is committed to reducing the impact on areas such

as forests, wetlands, and other ecologically sensitive areas in the environment (Soderlund et al., 2008).

Municipal jurisdictions and academic researchers strive to analyze best practices and successful strategies to increase transportation system efficiency; manage negative impacts, such as crash costs, land use, and harmful emissions; and make progress toward sustainable goals. Depending on the background and focus of some researchers and practitioners, sustainability can be categorized into four pillars. The additional aspect that can be included as the fourth pillar is called technical. The technical aspect is more commonly applied in the sustainable energy research and teaching area. This study, however, focuses on only three aspects of the sustainability development concept. Figure 2.1 shows the four pillars of the sustainability concept.

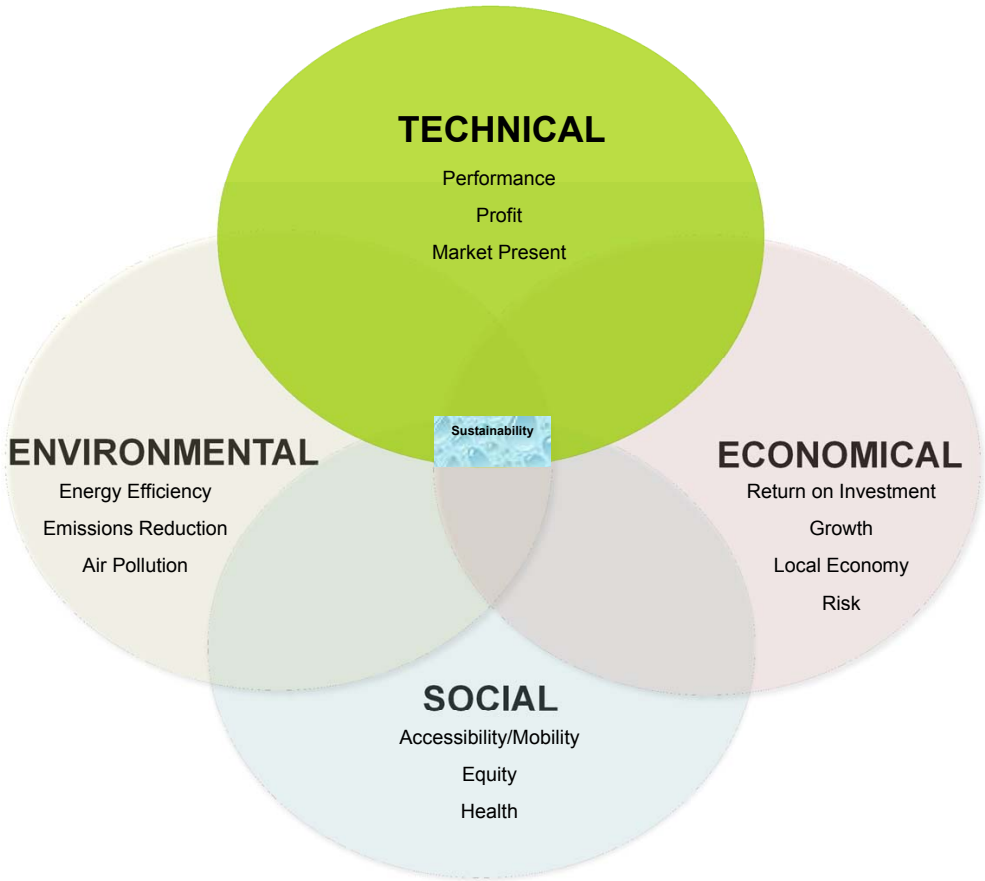


Figure 2.1. Venn Diagram of Sustainability Development.

There exist a number of sustainable indicators. Litman (2005) presented a list of indicators that can be investigated when focusing on the sustainability concept. This study can be fitted into the studies that have explored the following sustainable indicators on that list: vehicle emissions, availability and quality of affordable modes, service delivery unit costs compared with peers, human exposure to harmful pollutants, walkability and bikeability, and per capita emissions of GHGs. The following three sections summarize some of the recent studies that have focused on the sustainable concept, with different objectives.

2.1.1 Economic Principles

Transportation investment and land development in outlying have the potential to increase property values and decrease traffic volume, thus decreasing travel time (Knaap et al., 2001; Cervero and Duncan, 2002; Graham, 2006). Aschauer (1990) pointed out how future transportation investment, thus fewer vehicles and their attendant environmental impacts, could contribute to air quality improvement and, by extension, to health, economy, leisure quality, and safety. According to *Light Rail Now* (2002), light rail transit is a strong tool to counter urban sprawl.

2.1.2 Social/Equity Principles

Adoption of sustainable transportation by commuters and other interurban travelers has a direct impact on quality of life: decreased traffic congestion, due to increased reliance on public transportation or use of energy efficient vehicles, would have a salutary effect by decreasing air pollution. Citizens could devote time formerly spent in commuting to community service or to family and friends.

Focusing on the case of the city of Detroit, a number of neighborhoods were far from employment locations which take the opportunity of residents from those neighborhoods to a certain locations due to transportation to the lack of public transportation or long commutes that led to fatigue and discouragement. Ong and Blumenberg

(1998) in their study explored the obstacles of workers's accessibility to transportation to explore employment opportunities. Haynes et al. (2005) measured quality of life and also evaluated its relation to sustainable transportation alternatives and the potential implications for informing policy. Frank (2000) studied the implications of how land use and travel behavior affect quality of life, and the study provides some strategies to increase the relative utility of walking and transit. Shafer et al. (2000) found that three urban greenway trails have improved the quality of life of Texas commuters who travel to work and leisure activities via trails.

2.1.3 Environmental Principles

Several researchers have focused on the environmental science aspect of sustainability: energy; health concerns arising from degraded air quality; direct and indirect GHG emissions from land use; and CO_2, NO_x, and VOCs particles that lead to global warming potential (GWP). Petroleum is the source of many uncleaned fuels (e.g., gasoline, jet fuel, diesel fuel) used in the world to operate motor-based vehicles. Nevertheless, Black (1996) stated that petroleum has no future and suggested that the United States cooperate with Europe and perhaps Japan to solve the sustainability problem. Among the most recent studies that can be categorized in the environmental aspect, Eberle and Von Helmolt (2010) analyzed the conventional fossil fuel or bio fuel internal combustion engine that can be used to power electric vehicles. In their study, two major alternatives were discussed, namely electrical energy storage using a battery and electrical energy storage using chemical form and application of a fuel cell. Besides the advantages of the alternatives, they also have limitations.

2.1.4 Sustainable Development and Sustainability Literature Review

Since the development of the sustainability concept, a number of academic and technical studies have examined the topic. This part of the literature review examined areas within the sustainability concept that have been studied to formulate the

research topic focus in this research. This section of the report summarizes sustainability studies that have been published or to fulfill master's and doctoral degree requirements. The summary of this section is divided into two parts. Section 2.1.4.1 examines only sustainability studies that were performed to fulfill degree requirements from 1970 through 2016. Section 2.1.4.2 summarizes studies that address the application of the sustainability concept in the real world.

2.1.4.1 Academic Sustainability Studies

A number of sustainable development and sustainability research studies have been completed in a broad range of disciplines. Others have differentiated sustainability development from the sustainability concept based on how the latter concepts are being applied within a field or area. O'Grady (2007) defined sustainable development in relation to the growth of human population that essentially implicates economics, while interpreting the definition of Geerlings (1999) for sustainability, one can state that sustainability focuses on the life-cycle of a system over an endless amount of time. Dryzek (2013) identified a number of discourses to articulate major sustainable development issues. To consider sustainable development, Costanza (1992) created a foundation for an integrative framework. By evaluating the relationships among economic systems and ecosystems, Jabareen (2004) presented metaphors to interpret sustainable development. Mol (1995) and Reijnders (1998) studies also focused on sustainable development to investigate the connection of technological metaphor.

Frankic (1998) focused on sustainable development in coastal regions to develop a generic framework that incorporated biological, geological, chemical, physical, social, and economic factors. In Frankic's dissertation, an integrated geographic information system (GIS) and remote sensing technology were used in the methodology to reach his findings. Trisoglio (1996) seeks to examine sustainable development (SD) to assist with the decision-making process in a complex world. Two policy models that ac-

counted for complexity and uncertainty within different scales in the SD debate were developed.

The global per capita demand on energy is increasing (Johansson, 1993; Lazarus et al., 1993), which might cause the larger complexity of environmental problems (Holmberg and Karlsson, 1992). Attah (2010) focused on global efforts to achieve the concept of environmental sustainability in developed and developing countries, namely the United States, China, and Switzerland. Attah's thesis also brought insights on some strategies that other developed countries are using to achieve the sustainability goal so other countries can look into using them. Furthermore, his thesis outlined other significant efforts to be investigated at a global level to achieve the desired balance. Hall (2006) in his dissertation investigated the sustainability development concept to understand and applying the said concept in transportation planning and decision making. In his dissertation, a decision-support was investigated to inform policy makers how sustainability can be integrated when creating transportation policies and programs in the United States.

Dhakras (2004) studied the development of sustainable transportation systems parameters by analyzing Mumbai, India. In his dissertation, transportation problems in Mumbai were identified and their causes studied to measure and suggest achievable measures for sustainability. Zuidgeest (2005) evaluated sustainable transportation development using a dynamic optimization approach. Smith III (2009) explored how the sustainability concept can be taught within the university system.

Oswald (2008) in her thesis analyzed the sustainability of transportation investment rating based on a corridor in the state of Delaware. The main objective of Oswald's thesis was to promote sustainability development within the field of transportation with the design of a green design rating system for transportation.

Chaabane (2011) explored the sustainable design of supply chain using a multi-objective mixed-integer linear programming approach to reach the findings. Rader-

bauer (2011) investigated the importance of sustainable business practices using a mixed method approach. One of the interesting points from Raderbauer's thesis (2011) was that communication between public and private sectors when advertising sustainability to consumers should be improved. Berry and Ladkin (1997), Dewhurst and Thomas (2003), and Horobin and Long (1996) found that the communication between the private and public sectors is sometimes ineffective, while the Bramwell and Alletorp (2001) and Forsyth (1995) studies found that no agreement regarding the main responsibility for sustainable development lies with the private or public sectors.

Rangarajan (2012) explored sustainability development with multifold objectives to assist decision-makers with tools and frameworks that can be used to examine sustainable policies. Rangarajan (2012) considered three transportation projects to develop a framework analysis that stakeholders can use as a strategic tool. Barrella (2012) examined strategic planning when investing in a sustainable transportation system. To reach the findings, a self-assessment tool was designed for transit agencies to use as a guide. To validate the designed tool, seven state departments of transportation (DOTs) were used as trials to provide feedback in strengthening the tool for future use.

Arora (2014) investigated strategic sustainable supply chain management by focusing on the following aspects: manage, measure, mitigate, and market. In Arora (2014), a multi-method approach that involved linear programming techniques with secondary data was developed to reach the findings.

Tins (2003) evaluated the urban transportation system in Hong Kong with the application of the theory of "ecological modernization". Singh (2014) analyzed the road network of the University of Rhode Island's (URI) Kingston campus with the used of Micro PMS. The pilot study was carried out using the condition data of the different pavement sections of the URI Kingston campus.

2.1.4.2 Practitioners Sustainability Studies

Boyle (2006) predicted that the doctrine of sustainable development would be based upon the doctrine of global trusteeship. The adaption of sustainable development since 1987 has being popular and beneficial in different areas of transportation and other fields. Goldman and Gorham (2006) stated that sustainable transportation efforts were categorized into two general clusters of work. Researchers have focused on the sustainability concept when designing, operating, and maintaining public transportation systems for different reasons. Stakeholders and policy makers have used sustainable development to measure the performance of the three aspects and strategies.

The implementation of the sustainability concept in the field of public transportation has attracted the attention of the world and, more precisely, researchers. Eblen and Eblen (1994) stated that sustainable development can be defined as the management of the human use of the biosphere so that it yields to the greatest benefit of sustainability. Among all those studies that have incorporated the sustainability concept to reach their findings, each one of them might have analyzed all three aspects concurrently or one of them. Other studies have summarized transit network design and sustainability or sustainable commute, such as Zhou (2012) and Miller et al. (2016). Sinha (2004) identified a number of indications to consider when assessing sustainability of an urban transportation system.

Transportation engineering designers, modelers, and researchers have focused on several key elements to design and plan transit service, which others might call decision variables (e.g., stop spacing, headway/frequency, vehicle occupancy, fare). Lyle (1996) stated the environmental planners's goal is to place the development of land into cities and also the protection of natural systems into a state of vital equipoise so urban sustainability should be pursued. When modeling public transit, researchers have considered optimizing design variables to look at the trade-offs or effects on

different transit characteristics and transit variables. The environmental impact indicators that have most often been investigated by researchers are: land consumption; energy or consumption of renewable energy per capita; emissions of local air pollutants, namely, CO, nitric oxide (NO), and nitrogen dioxide (NO_2); and GHG emissions such as CO_2, methane (CH4), VOCs, and volatile hydrocarbons.

Some studies simply provided the key dimensions to optimize public transit. Kenworthy (2006) provided 10 transportation and planning dimensions to analyze sustainable city development. Litman (2011) investigated public transportation as a strategy to reduce energy conservation and emission reduction. A case study of the Guangzhou BRT was presented by Hughes (2012) to explore the effects of emissions on the vehicle speed.

Burnett et al. (1998) investigated the effects of air pollution and mortalities in Canadian cities. Gauderman et al. (2005) and Lipfert and Wyzga (2008) explored the public health effects of air pollutants due to traffic congestion in European cities.

Rapp and Gehner (1967) focused on optimizing transfer delays in one of their studies within the planning phase of public transit. A graphic interactive computer approach with an optimize transfer delays was applied. Using a case study in Switzerland to apply the model, the total transfer delay times were found to be reduced by 20% without affecting the operating costs.

Newell (1979) focused on dispatching policies for transit routes (e.g., trains and buses) to minimize the waiting time of passengers using an analytical methodology with the vehicle size as a constraint. Similar to Newell's study, Salzborn (1970) also studied optimizing the fleet size of railcars using a set of linear zero-one programs for a railway system while also minimizing the overall driver time, which would also minimize the cost of labor. Furthermore, Salzborn (1972) studied optimization of bus scheduling using a mathematical approach to minimize waiting time of travelers and the frequency of buses per single route.

Borck (2008) evaluated the political economy aspect of urban transit. To reach the findings, Borck used a selective survey approach instead of modeling. Watkiss and Downing (2008) in the United Kingdom evaluated the social cost of carbon (SCC) using a mixed approach: literature review, FUND and PAGE modeling, and the knowledge of elicitation experts. Among others who have focused on SCC, Anthoff (2004) and Anthoff et al. (2009) analyzed the equity weighting of damage costs of climate change. Anthoff (2004), and Guo et al. (2006) explored the uncertainty of SCC and discounting. Although the latter studies did not directly focus on public transportation. Glaeser and Kahn (2010) focused on the effects of carbon dioxide emissions from home heating, housing electricity usage, private vehicles, and transit, using a quantitative methodology. The latter study revealed that Texas had higher emissions than California. Parry and Small (2009) investigated urban transit subsidies to find out subsidies should be reduced. Parry and Small determined empirically tractable formulas to optimize pricing of peak and off-peak rail and bus transit passengers. Mohring (1972) investigated the magnitude of mass transit scale economies that can help lower bound the optimal transit subsidy policy of an urban bus transportation. Ibeas et al. (2010) studied optimized bus stop spacing in urban areas, with the main objective of minimizing the social cost of using public transportation. Using a bi-level optimization approach, results from Ibeas et al. showed that passengers' mode choice can be affected based on the number and the location of the bus stop. However, the authors do not prove travelers's behavior on choosing a public transportation mode, nor at what number of stops passengers's mode choice is being affected.

Murray et al. (1998) focused on the impacts of public transportation accessibility to the overall success of the transit system in Australia. The accessibility of public transportation can be interpreted to the cost of using the service or the proximity or the availability of the service to regional travelers. Murray et al. (1998) did not evaluate the accessibility of public transportation using analytical methods, but rather

using previous studies that have investigated the access of public transportation. Haynes et al. (2005) analyzed the social impact of having more private transportation on the road. The latter study revealed a number of methods to assess sustainable transportation and the quality of life of the passengers.

Land use consumption for public transportation infrastructure can be fitted under one of the sustainability indicators. Land use can also be overlapped under the environmental and economic aspects of sustainability, based on the areas the investigators choose to investigate its impacts. Paulley and Webster (1991) performed an overview of a number of models that analyzed the effects of transportation land use in several areas, to comment on the lessons learned from those articles. At the conclusion of the review, Paulley and Webster's substantial insights were provided on the policies that were evaluated in those articles.

The economic aspect of said concept has been evaluated with studies that are focused on population density, economic efficiency, employment, and gross domestic product (GDP) per unit of energy use. Uher et al. (1984) studied energy cost reduction using data from the Washington Metropolitan Area Transit Authority (WMATA). Buehler and Pucher (2011) investigated the effect of making public transportation financially sustainable. The authors stated that Germany's public transportation cost was increased after applying the strategy of organizational restructuring and outsourcing to newly founded subsidiaries. The qualitative and quantitative analysis in the methodology of their study involved a wide range of data sources. Some positive impacts of the strategy were the increase in monthly revenue and improvements in quality of service, which might be the cause of their ridership growth. Last and most importantly, the strategy resulted in restrictions on car use in Germany. As a consequence, benefits of workers and wages were negatively impacted.

2.1.4.3 Relationship between Sustainability and Transportation Engineering

Sustainable transportation can hold a number of definitions, but the most common references to sustainable transportation are based on the definitions of the Organization for Economic Co-operation and Development (Ypsilanti and Gosling, 1997; Naganathan, 2013; Gilbert and O'Brien, 2005). Despite the different definitions of sustainable transportation, Williams (2005) pointed out that all of those definitions can be summarized into one common goal: meeting the social, environmental, economic, and mobility needs of the society. The field of transportation engineering involves all three aspects of sustainability. Regulations are being filled through policy making to achieve the goal of planning and designing sustainable transportation systems. With the regulations in place, stakeholders and transit users are encouraged when making decisions that are equitable, environmentally friendly, and economical. Chairatananon (2002) explored the relationship that exists among transportation and sustainability.

To address the concept of sustainability in transportation systems, routes, networks, or corridors, a number of studies have focused on some sustainable transportation indicators (Nicolas et al., 2003; Gilbert et al., 2003; Mihyeon Jeon and Amekudzi, 2005; Zegras, 2006; Litman, 2005; Li et al., 2010; Shen et al., 2010; Castillo and Pitfield, 2010; Doody et al., 2009; Litman, 2009; Mascarenhas et al., 2010; Haghshenas and Vaziri, 2012). A number of indicators have been categorized when investigating public transportation within the three aspects. Deakin (2001) evaluated strategies for economic prosperity, environmental quality, and equity to identify the areas that need to be researched more to increase the patterns of sustainable development and sustainable transportation.

A number of researchers, including Litman (2005); Quaddus and Siddique (2011); Tanguay et al. (2010) have mentioned in their articles that the sustainable concept

has been summarized into three aspects. The implementation of sustainability in the field of transportation engineering has the potential of assisting in meeting the common goal of eliminating GHG pollutants in the environment. Some studies have focused on qualities and quantities of the sustainability concept. Gilbert et al. (2003) summarizes the positive effects of sustainability in the environment. On the social aspect, sustainable transportation can provide safe and equitable accessibility to public transportation. And lastly, sustainable transportation is affordable, efficient, and allow travelers to choose among several modes of transportation.

2.2 Transit Network Design and Optimization

For decades, transit network design problems have been studied using various approaches, such as stochastic, artificial intelligence (AI)-based, mathematical optimization, two-stage models, and heuristic algorithms.

City structure is the organization of land use in any urban area, allowing the identification of different sectors such as residential houses, businesses, and manufacturing. Economists, sociologists, planners, and geographers have created models, namely, concentric zonal, sectoral, and multiple nuclei, to show us different areas within a city. Considering different types of systems, such as linear, grid, hybrid, and radial/polar grid/spider web, makes the design and planning of each transit corridor exclusive. In addition, city structure can also be considered as playing an essential role in designing transit networks to accommodate citizens in a city.

Pattnaik et al. (1998) applied a genetic algorithm to transit route and frequency optimization. Similarly, Tom and Mohan (2003) proposed a genetic algorithm method to instantaneously design routes and frequencies, with the objective of minimizing both operation and user costs. Ceder (2002) investigated public transport network and route design and proposed a heuristic, demand-oriented method to redesign route and frequencies in two stages, which will help in lowering operation costs. Wan and

Lo (2003) used a mixed-integer model to help the problems of changing and routes and frequencies of existing transit networks.

Gao et al. (2005) focused on optimizing user and operator costs of public transportation using a bi-level programming model with a transit assignment model as the lower bound of the model for stimulating path choices. Fan and Machemehl (2004) also analyzed the transit network design problem (TNDP) with the formulation of a multi-objective non-linear mixed-integer model to minimize operator cost and unfulfilled demand, and user cost. Schöbel and Scholl (2006) studied the planning problems of TNDP using an integer programming model, considering transfer penalties as part of the minimization of public transportation costs. Cipriani et al. (2006) suggested an approach to solving multi-modal TNDP. Some studies focused on some specific modes, such as Marin and Jaramillo (2008) and Marín and Jaramillo (2009), who focused on maximizing public transportation demand of rapid transit network design with budget constraints using a Benders decomposition algorithm and a heuristic method.

Yu et al. (2009) evaluated bus frequency optimization problems to minimize total travel time, considering overall fleet size. Laporte et al. (2010) studied the problem of designing a railway transit network with link failures with a game theory framework. Gallo et al. (2011) explored TNDP, assuming elastic demand. Desaulniers and Hickman (2007); Kepaptsoglou and Karlaftis (2009); Guihaire and Hao (2008), and others all focused on TNDP. But Guihaire and Hao suggested that all the problems can be recognized and categorized on the basis of the decision variables measured. Newell (1979) evaluated the grid structure of transit network systems. Tirachini et al. (2010) focused on the structure of the transit network, namely radial systems, to compare light rail transit, metro heavy rail, and bus rapid transit. Daganzo (2010) analyzed transit system design and operations with the hope of having public transportation

complementary to vehicles. Others, such as Sivakumaran et al. (2014), evaluated the influence of access mode of the choice of the transit mode.

Studies focusing on TNDP did not fully take into account the three aspects of sustainability: economic, social, and environment. Some focused on one, others on two aspects. Szeto et al. (2014), however, also evaluated the route network design and simultaneously analyzed the three dimensions of the sustainability concept. Szeto et al. (2014) stated that numerical analyses are used to explore the Pareto optimal between the three aspects of the sustainability concept. The latter study proposed an artificial bee colony (ABC) to test the network design solutions of the upper bound of the problem, while the method of successive averages and the Frank-Wolfe algorithm were approved to find solutions for the lower-level time-dependent land-use transportation problem.

Transportation land use has been studied by several researchers Los (1979); Yim et al. (2011); Szeto et al. (2010). Szeto et al. (2015) also investigated the road network design problem (RNDP) with focus on the sustainability concept and the interaction with land use transportation over years. In the latter study, Szeto et al. (2015) used the ABC methodology to investigate the network design solutions of the upper level problem, the method of successive averages (MSA), and the Frank-Wolfe algorithm. They proposed a multi-objective bi-level optimization approach to simultaneously evaluate the sustainable RNDP costs to reach the optimal network.

2.2.1 Multimodal Transportation Systems

Public transportation is enlarging and evolving as a vast area of concentration in transportation engineering, since more features and new high transportation technologies are being introduced to the market. To make accessibility easier to travelers, transit agencies are sometimes operating more than one mode of public transportation. With the operation of different transit modes in a city, travelers are more often

faced with travel mode decision making, while transit agencies are sometimes facing the transportation investment decision making to accommodate travelers with the most efficient mode(s) of transportation. To ease their decision making as well make public transit more attractive to users, researchers have explored different areas of public transportation by focusing on one single mode or more than one mode when researching. This section of the literature focuses on different areas that researchers and practitioners have investigated to bring insightful information to the world and more precisely to those who are interested in or use public transportation.

With smart-growth and new riders, it is common sense for a district bus corridor to introduce a dedicated bus lane, an express bus or bus rapid transit, and sometimes light rail transit. However, those options mentioned previously, more specifically DBLs, express buses, and bus rapid transit, do not seem to always be the solution to traffic congestion, as those modes take away a lane from regular traffic. Eichler and Daganzo (2006) investigated bus lanes with intermittent priority and provided strategy formulas and an evaluation using deterministic analysis techniques of kinematic wave theory. Eichler and Daganzo first found that bus lanes with intermittent priority (BLIPs) do not expressively reduce street capacity, but traffic delays are increased. The findings also summarize the factors that can be evaluated to determine if intermittent systems save time: the bus frequency, the traffic saturation level, the improvement in bus travel time achieved by the special lane, and the ratio of bus and car occupant flows. In case DBLs cannot be operated, the results the results show that BLIPs can save both bus and vehicle passengers as much as 20 passenger-minutes per bus kilometer.

Zhu (2010) studied DBLs and intermittent bus lanes (IBLs) with properties of urban traffic flow. Zhu found that IBL is more advantageous than DBL, as IBL not only improves car flow, but it also upholds the car flow at a higher level at the same time than does DBL. However, a disadvantage of IBLs was its interruption of

traffic. In Zhu's study, the concept of public transportation priority and the cellular automaton traffic flow model were used to reach the above findings. Arasan and Vedagiri (2009) developed a micro simulation of heterogeneous traffic flow to evaluate the effect of urban roads with provision of reserved bus lanes. The findings of Arasan and Vedagiri's study showed that dedicated or exclusive bus lanes can be introduced on urban roads without adversely impacting the level of service of other modes on the road.

2.2.2 Optimization Algorithms and Heuristics Methodology

Kuah and Perl (1988) focused on optimizing feeder bus routes and bus stop-spacing using an analytical model. Similar findings compared to previous studies that optimizing feeder bus routes for accessing a rail line station were found in Kuah and Perl. Vuchic (2005) analyzed the operational aspect of urban transit. Ceder (2007) also focused on public transportation planning and operation to optimize transit scheduling passenger demand and assignment transit service. Liebchen (2007) optimized public transportation periodic timetables. Fu et al. (2003) investigated real-time optimization for dynamic scheduling of transit operations using a non-linear programming approach to minimize the overall operators and travelers' costs. Chien and Qin (2004) explored bus stops or station positions to improve the accessibility of transit. Lindner and Zimmerman (2000) explored optimizing public rail schedules, and Su et al. (2013) focused on subway train timetable optimization to reduce operation costs and energy consumption. Teng and Yang (2006) studied vehicle dynamic dispatching problem for one bus rapid transit line in a system using a real-time operational control. Kulyk and Hardy (2003) explored the enhancement of bus rapid transit systems with intelligent transportation system (ITS) devices. Galicia et al. (2009) investigated infrastructure and features that make bus rapid transit systems successful in a U.S. city.

Several transit agencies think that an improvement in transit quality is more likely to attract travelers to give up their personal vehicles and adopt public transportation as their daily mode of transportation. Conversely, the case study by Poudenx (2008) found that public transportation attractiveness has no effect on personal vehicle drivers but does encourage non-motorized travelers to adopt public transportation. In addition, Chester and Horvath (2009) show that emissions per passenger mile traveled (PMT) is highly dependent on ridership. In other words, attracting more passengers will also increase emissions. Therefore, a trade-off arises, as one of the transit agencies' goals is to attract more travelers. Should they continue implementing more features to increase public transit ridership and ignore the increase in emissions? Or should they give more importance to the environmental aspect of the sustainability concept? These questions left stakeholders in a tough dilemma, as public transit agencies' main goal is to provide the most efficient service to the population with progress toward sustainability goals.

Allport (1981) investigated the economic cost of the maintenance, administration, and capital operations of three different public transportation systems on a common basis. In Allport's study, cost models were developed for three transportation modes: light rail transit, bus, and metro. The three transportation mode models compare the total social cost to determine the least economical mode, based on different demand levels in different situations. The 1978 annual accounts were used to collect primary data to reach the findings of the study. This collected data was carefully interpreted. The dominant cost was the labor cost, representing a total of 58% of all costs.

In Allport's 1981 study, all three models used an existing 8 km radial corridor using realistic demand characteristics and supply. The results show that up to a level of 3,750 of the demand rate, the bus seems to have the lowest operating cost. The light rail transit was found to have the lowest operation cost within a demand range of 100,000 to 175,000. Lastly, the metro demand capacity was above the demand range of

the light rail transit. Taking into account the user costs or the value traveler's overall travel time, the bus appeared to be the least expensive with the least operating cost, up to a 50,000 demand level.

Griswold et al. (2013) explored the trade-offs between costs and GHG emissions in the design of urban transit systems, as recent investments had not fully focused on the potential of network and operational improvements, namely, headways, route spacing, and stop spacing, to reduce transit emissions. Their model emphasizes the Pareto frontier concept to design an idealized transit network. In addition, their model could be useful to transit agencies that wish to improve existing transit networks or that need guidance with selecting suitable transit modes and design attributes to implement in new transit systems. A many-to-many travel pattern with a uniform distribution of the passenger demand from origins to destinations was applied. Several scenarios were run for each selected mode in the study. The model examines small and large cities using a grid city structure with different modes, such as light rail,bus rapid transit,metro heavy rail, and bus. The results show that bus rapid transit is more cost effective only in terms of operations and user costs in large cities. Buses and light rail transit were found to be more cost effective in terms of operational, user, and emissions costs in small cities.

In Griswold et al. (2014), the authors investigated the greenhouse gas effects when the level of service demand in urban transit systems is lowering. Their article is based on Griswold et al. (2013) article where continuous approximation models with fixed demand were used to optimize the design and operations of transit systems in regard to costs and emissions. The authors incorporated travel time elasticities in their model to account for passenger shifts from transit to personal automobiles.

Following Griswold et al. (2014), Cheng et al. (2016) also investigated trunk transit systems with focused on lowering reducing greenhouse gas emissions. Similarly, the latter study focused on the same design variables attributes that Griswold et al.

(2013) and Griswold et al. (2014) with related formulation that was performed in Sivakumaran et al. (2014). However, in Griswold et al. (2014), users' were assumed to walk to reach the studied trunk technologies stops or station while in Cheng et al. (2016) a hierarchical trunk network to accommodate user to reach trunk stations or stops using feeder buses. A comparison of both small and large cities were made to apply the approach in Cheng et al. (2016) into real world cities and to also evaluate the impacts of small and large cities on GHG emissions. However, a hierarchical grid trunk system is more likely to increase the capital cost of the agency of being buses to run the feeder buses.

Additionally, the study does not take into account the coordination of the headways of both system to avoid users of spending twice of the headway if they miss the feeder bus. Missing the local buses might ending in low demand density for both trunk and feeder systems and also increase GHG emissions. Hierarchical systems require travelers to make several transfers which might push away travelers who do not feel comfortable making several trips with transfers end up adopting a more convenient mode of transportation which sometimes worsen the environment or the air quality.

Griswold et al. (2013), Griswold et al. (2014), and Cheng et al. (2016) analyzed the operational characteristics of urban transit systems' effect on both the cost and GHG emissions; however, their study did not take into account different operational modes (cruising, idling, and acceleration/deceleration) of the selected transit modes. In addition, their study focuses on only one type of city structure; some of the selected modes would have performed better in a different city structure. Furthermore, the study did not take into account variable passenger demand distribution from origins to destinations.

Among all studies mentioned in this document, not a single one focused on optimizing public transportation operations with the incorporation of the different characteristics of the operation modes, cruising, idling, and acceleration/deceleration in the

driving cycle, and none simultaneously analyzed the effects of public transportation in a linear corridor based on the three aspects of the sustainability concept. Griswold et al. (2013) is the study that is the most related to this study. That makes this study unique and appealing to public transportation stakeholders and decision-makers.

2.2.3 Public Transportation Cost Models

Several cost models to compare transit modes in the academic world have already been developed. This aspect of this study seeks to identify parameters that are important when comparing transit routes in different regions or zones across North America. This study also aims to focus on planning and designing sustainable transit corridors by using analytical cost models using real-world data instead of analyzing the system as a whole, starting with Rust (1987), who focused on unknown primitive parameters to study Zurcher's expectations of the future values of the variables, the expected costs of regular bus maintenance, and customers's goodwill costs of unexpected failures. In Rust's study, an investment model that used a micro-theoretic was employed to reach the findings. The findings of his study showed that the model can answer a wide range of what-if policy questions. Bhatta and Drennan (2003) looked at the long-term economic benefits of investing in transportation infrastructure, although this study did not focus only on public transportation, but instead on transportation in general. The approach to answer the research question of their study does not rely on analytical models, but rather on reviewing previous economic studies that had attempted to tackle the same or similar research questions. Their methodology is organized into five categories of economic benefits. Their findings reported two terms of economic benefits of public investment in transportation. Those two benefits are short-run and long-run benefits.

Tirachini et al. (2010) used a radial transit network to explore the optimization of the total operator and user costs of three-trunk technology, such as light rail, metro

heavy rail, and bus rapid transit. Using Australian data to perform the case scenario analyses, their findings show that metro heavy rail and light rail might have a total lower cost than bus rapid transit only if they are able to operate faster than bus rapid transit, focusing on their free-flow and commercial speed. This explains the reason why their results also show that a high standard bus service will be the mode that is most cost-effective, based on the speed difference and operating and user cost.

2.2.4 Transit Agencies Low-Cost Option Strategies to Attract Passengers

Over the last few decades, researchers have dedicated time to explore ways to design safe and cost-efficient public transit systems. Different approaches can be used to improve overall transit productivity. In some countries, transit agencies have improved roadway design and traffic regulations, while others have focused on transit signal priority (TSP), other rapid transit modes (LRT and BRT), transit network structure, transit system operations, and separate ROW. However, some of those strategies are, first, exorbitant and do not provide certainty that transit vehicles will be moving faster. Among those strategies mentioned, there exist several strategies that have been used as enhanced options to provide better public transit service at lower cost.

Public transit signal priority (PTSP) has been considered one of the low-cost options that transit agencies have used to diminish the overall travel time when using public transit. A number of researchers have investigated the benefits of giving buses priority at traffic signals. Hunter-Zaworski et al. (1995) have evaluated the benefits of using traffic signal priority in the city of Portland, Oregon. The benefits of using TSP in the latter project was assessed by comparing before-and-after applications of the TSP. Garrow et al. (1997) have developed and evaluated a wide range of traffic signal priority strategies using the TRAFNETSIM micro-simulation model. Others, like Furth and Muller (2000) in Eindhoven, Netherlands, have investigated

the conditional TSP to diminish traffic disruption. The findings of the Furth and Muller (2000) have shown a strong improvement in schedule after the installation of TSP. Barton (2003) has evaluated TSP options for rapid transit and light rail transit in the city of Richmond, Virginia, with a strategy of finding the best values for the length of the green extension given to the transit modes and the implementation of phase skipping and unconditional. Barton's findings revealed lower travel times for an LRT system than an express bus by using shorter average dwell times for light rail transit vehicles at the stations or stops. Moreover, the findings suggested modifications of far-side transit stops to limit transit delay and travel times. Nash (2003) studied the implementation of TSP in Zurich, Switzerland, with the help of interviewers who answered a survey of public officials. A number of key findings were found, as follows: no green time was wasted after the application of the TSP; Zurich's livability improved; and its transit system has become effective and attractive to travelers.

Chang et al. (2003) have looked at the service reliability impacts of TSP strategies for bus transit. Statistically significant simulations improvements in bus service reliability and bus efficiency were found to be 3.2% and 0.9%, respectively. Additionally, the overall delay of the corridor was improved by 1% on a vehicle basis or 0.6% on a person basis. Vlachou et al. (2010) presented a comprehensive comparison to show the differences in transit priority planning and deployment in small- and medium-sized cities and metropolitan areas.

2.2.5 Public Transportation Greenhouse Gas Emissions

Despite the extensive research in the transportation sector that has focused on climate change and air pollutants, there is still a need to explore the potential impacts of the transportation sector on climate change using new or modified methodologies to better understand key relationships among air quality and emissions. While the trans-

portation sector continuously accounts for the largest share of GHGs, transportation GHG emissions need to be sustainably modeled to find the trade-offs among different sustainability indicators and what policy responses or questions should be developed to better manage and mitigate travel emissions.

Emissions contributed by public transportation have been evaluated. Hickman et al. (1999) evaluated methodologies to calculate emissions from rail-based transport modes. Starting from evaluating methodologies to calculate emissions from all transport modes, including rail, globally to emissions inventory from city to city Dodman (2009) to reduce global GHG emissions, still GHG emissions are a growing concern to the population. Tzeng et al. (2005) with a multi-criteria analysis investigated alternative-fuel buses for public transportation. The study found that hybrid electric buses were the most suitable for Taiwan for the short and long term. Shapiro et al. (2002), Puchalsky (2005), Messa (2006), McMullen and Noh (2007), Zhai et al. (2008), and Chester and Horvath (2009) evaluated comparisons of GHG emissions and life-cycle analysis between different public transportation modes using different methodologies.

Gallivan and Grant (2010), in the TCRP Synthesis 84 Report, described strategies that transit agencies can adopt to further reduce GHGs emitted while simultaneously accomplishing other significant goals using strategies that can result in a growth of ridership and an overall improvement in transit operations efficiency. However, among the strategies or approaches suggested in the TCRP report to reduce GHG emissions, not all were reported to be cost effective as well as effective at reducing GHG emissions. Some strategies and approaches used in the study by Gallivan and Grant (2010) are quite similar to those used in the study by Stasko and Gao (2010) that focused on reducing transit fleet emissions through vehicle retrofits with an integral programming module that minimized operational costs, plus penalties for emissions, using capital budget as a constraint. McGraw et al. (2010) also provided

strategies to be used by transit agencies to reduce operational GHG emissions and energy use. Based on McGraw et al. (2010), vehicles providing transit service used the majority of energy and emitted the majority of GHG emissions. For that reason, most of the strategies presented in their report are related to transit vehicle fuels and maintenance efficiency. The initiation of bus rapid transit in Jakarta, Indonesia, has proved that bus rapid transit is capable of reducing transportation emission as well as providing an alternative to congested streets (Ernst, 2005).

Among the studies that have investigated emissions from public transportation, when analyzing single mode in comparison to different modes of transportation, only Zhai et al. (2008) have fully focused on the three dimensions of the sustainability concept in their approach.

2.2.6 Environmental Emission Pollutants Costs

Despite the policy of charging travelers based on the number of daily miles driven, the vehicle miles traveled (VMT) of personal vehicles in several countries is increasingly accelerating, which results in exceptionally high costs worldwide in many circumstances, such as high car insurance, health care coverage, accidents, and human lives lost. Researchers have considered level of service, average congestion delay, average traffic speed, and other measures to evaluate traffic congestion. Additionally, smart strategies that have the potential to take private automobiles off the road have been recommended. But to obtain a clear understanding on how to record the progress of traffic emissions reduction based on a reduction of VMT, it is the author's opinion that there should be a formula that can evaluate the percentage of emission costs reduction based on the percentage of VMT reduction. Indeed, the latter becomes a policy question that addresses environmental protection resources and the Department of Energy (DOE) to pass a regulation that can assist in meeting poten-

tial global warming goals. The formulation can serve as a guide to monitor traffic emission reductions.

Back in 1985, the United States government had announced NO_x emission standards for transit buses as well as heavy duty diesel vehicles. Stricter standards for particulate matter emissions were applied to urban bus engines (Schimek, 2001). Some studies within the emissions sector of public transportation have investigated the use of federal subsidy policy to convince the efficient use of public transportation and attract more passengers.

McMullen and Noh (2007) applied a directional distance methodology to show the importance of accounting for a transit agency's goal of reducing vehicular emissions and production of vehicle-miles. McMullen and Noh included 43 single-mode U.S. bus transit agencies from 2000 to investigate their research question. Their findings revealed that 22 out of the 43 transit agencies were found to be efficient if the goal of emission reduction was considered, while 5 transit agencies were found to have inefficient performance when the goal of minimizing vehicular emissions was not included.

Woodcock et al. (2009) investigated the public health benefits when strategies were used to reduce GHG emissions from urban land transportation. They compared the GHG emissions of two different cities to assess the benefits of reducing GHG emissions on the public health. Their findings revealed a combination of benefits from the use of lower-emissions motor vehicles and active travel habits of 7439 disability-adjusted life years (DALYs) in London, UK, and 12995 in Delhi, India. Litman (2003) explored how transportation decision makers can support public health objectives to reach the goal of reducing crashes, reducing pollutant emissions, and also increasing physical activities, which might be another cost-effective strategy of improving the public health. Van Vugt et al. (1996) focused on analyzing the travel mode selection judgment. The latter study was based on comparing public transportation with

private vehicles when making a trip. Their findings identified that a number of combinations of characteristics, such as travel time and impacts of vehicles on the environment, were more effective in promoting public transportation because some users's travel mode preferences were often based on their social value orientations.

2.3 Light Duty Private Automobiles

Over the last decades, a number of major OECD countries such as the United States, Italy, Japan, Sweden, Australia, the UK, Finland, and others have taken the initiative to considerably reduce the necessity of using energy to fuel economic growth. The need for travel is concurrently increasing with economic growth worldwide, while the sustainability of transportation is sometimes referred as an environmental problem (Black et al., 2002) without considering the equity aspect among generations, people and nations (Greene and Wegener, 1997), and the economic aspect of roadway funding policies, which often lead to an increase in VMT. The CO_2 emission levels are predicted to rise from 369 parts per million to between 540 and 970 parts per million over the next century (Nakicenovic and Swart, 2000). It was found that that a full breakdown in the unsustainable relationship among transportation emissions and increasing incomes (Schipper and Fulton, 2003) and the world resources is projected to exhaust within 50 years (Oman, 2004). The projected CO_2 increase can be interpreted based on Watson's (2001) findings to be a global average temperature of between 1.4 and 5.8 degrees Celsius (Watson and Albritton, 2001). Some researchers stated that the goal of CO_2 stabilization is practically impossible if the growth in zero-carbon technologies or energy efficiency has not improved (Schafer and Victor, 1999). Stanley and Watkiss (2003) state that public transportation is found to be a better option to reduce CO_2 emissions per kilometer with an occupancy that is higher than three passengers .

Using a strategy that involves combining better technology, demand restraint, taxes, and regulations could finally lessen CO_2 emissions, the effects of the strategy on transportation and the wider economy is left unknown (World Business Council for Sustainable Development and World Resources Institute, 2001; Jahn et al., 2000). Geller et al. (2006) conducted an investigation for the state of California that focused on analyzing programs and energy efficiency policies that California has adopted. Chapman (2007) conducted a review to explore how behavioral change and technology can reduce the combustion of fossil fuels.

Bristow et al. (2004) stated that adopting hybrid and electric cars can be a better option in moving forward in reducing CO_2 emissions. Andrews (2006) in a review investigated the history of oil shade, tax incentives, and policy. Yan and Crookes (2009) focused on evaluating effective ways to measure GHG reduction in China by using different case scenarios to estimate the energy demand and GHG emissions from past and future years.

2.3.1 Light Duty Private Automobiles Operations Optimization

A number of studies have focused on operating cost using different methodologies. Most of those methodologies involve optimization. Khodayar et al. (2012) evaluated the hourly coordination of electric vehicle operation and volatile wind power generation in SCUC/ using a stochastic security constraint unit commitment model. The latter optimizing model allowed the author to minimize the expected grid operating cost. Rousseau et al. (2008) focused on reducing fuel consumption of plug-in hybrid electric vehicles (PHEVs). The findings of the Rousseau et al. study revealed that broad investigation of the whole design space might result in finding useful information about the operation of PHEVs.

2.3.2 Light Duty Private Automobiles Greenhouse Gas Emissions

An increase in VMT results in more highway capacity, land use, an increase in the price of fuels, as well as more GHGs emitted in the environment. A recent study by Ewing et al. (2014) using structural equation modeling with recent VMT data in urbanized areas analyzed the long-run relationship between transportation and land use from 2000 through 2010. Their findings showed a lower VMT per capita from the cross-sectional analysis model for the year 2010 in the areas where there were higher transit development densities and per capita use. Additionally, their findings from both cross-sectional and longitudinal models revealed that the primary exogenous drivers of VMT are population and income, although one of the limitations of their models was the exclusion of congestion measures in relation to vehicle travel and VMT.

One common goal of all sectors of the transit economy is to save energy and reduce GHG pollutants. Gallivan (2013), in the 106 TCRP Synthesis, provided other alternatives to transit agencies to reduce energy consumption, the potential magnitude of those reductions, and how to strategically plan and implement energy-saving measures. Several types of cleaner emission vehicles are being manufactured worldwide to decrease urban air pollution and gas/fuels used. In addition, to encourage the use of these cleaner vehicles, travelers who purchased these types of vehicles are able to deduct expenses on their annual income tax returns. One hindrance to wider adoption of cleaner vehicles is their high cost, so that bias violates the equitable aspect of the sustainability. Wu et al. (2015) studied road measurement of gaseous emissions and fuel consumption for two hybrid electric vehicles (HEVs), Toyota Prius hybrids in Macao, Hong Kong. The authors concluded that HEVs were a competitive technology option for the taxi fleet in Macao, with strong advantages in saving fuel cost for taxi drivers and mitigating NO_x emissions. Litman (2009) investigated air pollutant emissions from private automobiles, finding that CO_2, chlorofluorocarbon

(CFC), hydro chlorofluorocarbon (HCFC), and methane from fuel production and tailpipes have harmful effects on climate change and promote ozone depletion.

Wang et al. (2011) calculated CO_2 and pollutant emissions of passenger cars (PCs) in China based on a literature review, analyzing data from 2000 to 2005. The authors also investigated the development of policy measures intended to reduce emissions from PCs using three case studies to project future trends for PCs. The findings of their study showed that estimated baseline emissions of these pollutants were 3.16×10^6 tons of CO, 5.14×10^5 tons of HC, 3.56×10^5 tons of NO_x, 0.83×10^4 tons of PM_{10} and 9.14×10^7 tons of CO_2 for China's PC emissions, distributed evenly among provinces in China. By screening, processing, and analysis of protocols,(Frey et al., 2003) investigated on-road vehicle tailpipe emissions. In their study, only highway vehicles fueled by gasoline and a blend of 85% ethanol and 15% gasoline were analyzed. Their study found that during acceleration, the average emissions were found to be generally five times greater than during the idle mode for CO_2 and HCs and ten times greater for NO and CO.

Tzirakis et al. (2006) compared vehicle emissions and driving cycles of the city of Athens with ECE-15 and European driving cycle. Their study aimed at exploring fuel consumption and exhaust emissions from vehicles in the Athens basin, based on the effects of the driving patterns. The authors investigated a typical driving cycle process, such as accelerations and decelerations, as well as frequent stops. Real-world traffic data for all Athens road networks for a period of two years were collected using several types of electronic equipment, such as OBD II readers, GPS, accelerators, and others, seven days a week from 0600 until 2400. To measure and compare the emission of different pollutants, HC, CO, NO_x, and CO_2, with the fuel consumption, three passenger vehicles with different engines were selected, namely, a Citroën Sxara with a 1.6 L engine, a Mitsubishi Space Runner with a 2.0 L engine, and a Chrysler Cruiser with a 2.4 L engine. The comparisons of the emission and fuel consumption

measurements showed meaningful variations among the Athens driving cycle and the European driving cycles, excluding Athens. It was found that the European driving cycle is not the best method for the emission and fuel consumption estimation for passenger cars driving in the whole Athens network.

Zhai et al. (2009) have investigated vehicles powered by E85 fuel (an ethanol fuel blend) and gasoline to analyze the distinctions among fuel consumption and emission of flex-fueled vehicles. The methodology of their study involved both empirical and theoretical analyses. In the theoretical section of the methodology, the vehicle specific power (VSP), which is known as a valuable examining variable to estimate emissions rates, was used. The results have shown gasoline-fueled vehicles consumed less mass of fuel than E85-fueled vehicles for a given VSP mode. Furthermore, E85-based emissions and gasoline were found to be the same for CO_2 and lower for CO, while a higher value was found for NO, specifically in the case of higher VSP modes. Overall, the use of E85 was found as a better option compared to gasoline, as E85 is more likely to reduce CO emissions. However, E85 has a more adaptable effect on total hydrocarbons and NO_x emissions. The following sections separate the emissions studies that were evaluated into two cases of traffic network.

2.3.3 Static and Dynamic Traffic Network Studies

Elmi and Al Rifai (2012) researched passenger car exhaust emission pollutants when the vehicles are in the idling and accelerating modes within the vehicle driving cycle, in a congested traffic network. The methodology in their study involved the use of an Auto Gas emissions analyzer (AEA). The AEA is a portable instrument that is capable of measuring the emissions and other information of light duty vehicles. Similar to Frey et al. (2007); Elmi and Al Rifai (2012) found minimal emission pollutants of light duty vehicles during their idling and cruise mode of operations at all categories. However, the emissions found during the slow acceleration mode were

highest for CO, HC, and particles for light duty vehicles that have a mileage that is greater than 40,000 kilometers, which is consistent with what Pujadas et al. (2004) and Silva et al. (2006) had previously identified. Based on the final findings of (Elmi and Al Rifai, 2012), it was pointed out that the year or age of the studied light duty vehicles do not really matter when evaluating pollutant emissions of private light duty vehicles, but rather the average distance traveled of the vehicles.

Nesamani and Subramanian (2006) investigated the Indian driving cycle (IDC) of different road classes to estimate and evaluate the impacts of real-world driving on vehicle emissions. Their study approach focused on using the International Vehicle Emission model to study the network. The authors found that the classes of road do impact the emission rates, to the point of finding significant variations from one road class to another. In addition, local streets were found to have the largest emission rate impacts. To summarize, the authors found that the IDC did not represent real-world driving characteristics. The authors suggested that the potential driving cycle should contain pertinent driving characteristics, namely higher speed and acceleration, to compare to the real-world driving cycle.

2.3.4 Multimodal Transportation Greenhouse Gas Emissions

Acceleration/deceleration, speed, traffic signals, and the grade of the road are important factors that can significantly affect pollutant emissions of public transit and private automobiles on the road. Adopting lesser CO_2-emissions modes such as bicycles, walking, public transportation, and others does have the potential of diminishing traffic congestion from automobiles only if more passengers are willing to switch to the modes that are eco-friendly. Yet, several studies are still ongoing on how travelers's behavior can be more efficiently predicted to ease the decision-making process of public transportation stakeholders.

Rakha et al. (2000) suggested a framework that assisted in dealing with the impacts of intelligent transportation systems on energy consumption and vehicle emissions. The authors applied a series of multivariate fuel consumption and emissions prediction models directly to instantaneous speed and acceleration data and within a traffic simulation model of signalized intersection.

Shabihkhani and Gonzales (2013) studied life-cycle assessment (LCA) on how and what should be taken into account when evaluating CO_2 emissions in the field of transportation engineering. In Shabihkhani and Gonzales (2013), LCA of CO_2 emissions was evaluated and compared for each urban passenger mode that was studied (e.g., bicycles, public transportation, and passenger vehicles) based on the total demand. The authors' main objective was on the manufacturing of the vehicles and infrastructure construction and operation of the introduced modes in a multimodal transportation network. The findings of their study revealed that the CO_2 emissions originating from the manufacturing and operating of normal bicycles were smaller compared to the CO_2 emissions from passenger cars, light rail transit, and bus rapid transit. However, the results show that the CO_2 emissions from electric assisted bicycles were much larger than the emissions from bus rapid transit. The CO_2 emissions from taxis were found to be greater than those from passenger cars, because the travel distance of taxis is assumed to be double that of passenger cars in the considered zone of the study.

Silva et al. (2006) estimated fuel consumption and emissions of CO, HC, NO_x, and CO_2 using analytical models, assuming urban driving conditions. The authors selected three different models for which to perform the evaluation, namely, CHEM, EcoGest, and ADVISOR, which were previously developed by Barth et al. (2001) and Brooker et al. (2002), respectively. The results of Silvia et al. also predicted that accurate findings to within 10% to 20% can be obtained from emissions models in some cases.

Coelho et al. (2005) explored the impact of speed control traffic signals on pollutant emissions. To reach the findings of their study, the authors compared experimental and numerical data. One of their findings revealed that higher emissions are spread when signal control schemes resulted in stopping a larger fraction of speed violators. Nevertheless, when drivers's behavior modified the speed control of traffic signal that could result in a decrease in relative pollutant emissions.

2.3.5 Multi-Criteria Decision-Making Models

Lampkin and Saalmans (1967) concurrently investigated several variables of the overall system of a bus undertaking, using various methodologies. Conventional methods and linear programming methodologies were used to assist in assigning individual buses. The development of a heuristic model was determined to find the good route network, and to maximize service to passengers, allocation of service frequencies to route was performed. Lampkin and Saalmans found that the overall operating cost was reduced without having any effect on the overall level of service that is provided by the transit agency.

Basiago (1998) reviewed several alternatives of cultural models development of sustainability in many developing countries (e.g., Curitiba, Brazil, Kerala, India, and Nayarit). Basiago's findings showed numerous conceivable means by which social, economic, and environmental sustainability can be advanced in practice. Qin et al. (2013) investigated mixed transportation sustainable transit network design. Qin et al.'s objective was to optimize vehicle exhaust emissions, land-use scale, link load, and financial budget to decrease the resources exploited to meet the construction goals. Fedra (2004) developed a sustainable urban transportable modeling approach to investigated comprehensive transportation problems that can support and provide beneficial strategies for sustainable cities.

The application of the multi-criteria decision-making model (MCDM) in energy planning has been evaluated by several researchers. Lahdelma et al. (2000) analyzed energy and environmental planning and management methodologies with uncertainties. Hobbs and Meier (1994) made a comparison of MCDM methodologies to investigate the simplicity of feasible expected outcomes and applications.

Teng and Tzeng (1996) developed a multi-objective decision model to study traffic assignment and considering environmental parameters. Janić (2016) performed a multidimensional evaluation with focus on the infrastructural, technical/technological, operational, economic, social, and environmental performances of high-speed rail. Jani used a combination of descriptive and analytical methods to examine the performance based on the most significant factors. Sharma and Mathew (2011) evaluated the network design in India using a multi-objective methodology to identify the trade-offs among travel time and emissions. The authors used a non-dominated sorting genetic algorithm in their model. Sumalee et al. (2009) optimized a road-user-charging scheme to meet various policy objectives. Santos et al. (2009) accounted robustness and equity objectives with a multi-objective approach to analyze multilevel road network planning.

Liu and Nagurney (2012) studied the interplay of the heterogeneous decision-makers in the supply chain, which allows decision-makers with adequate information to forecast optimal plans with the hope of maximizing their profit. Corbett and Karmarkar (2001) compared a variety of supply chain structures and developed a framework of several tiers of decision-makers.

Pugnaire (1992) categorized the overall multi-criteria decision aid field in three components, namely, utility theory, outranking and interactive methods, and multiple attributes. The analysis in this study focuses on the multiple attributes of decision making when planning mass transit in a linear corridor with private vehicles. The fact of dealing with a number of criteria when planning or designing multi-modal

transportation, each study sometimes prioritized or focused on investigating one or more criteria based on their main goals or objectives. Donner (2008) and Ko (2009) both suggested that reliability of transportation, cost, traffic, security of road route, legal risk, risk of loss and damage should be the decision criteria in multi-modal transportation. Transit agencies and logistic companies have re-designed their network to reduce environmental impacts. Janarthanan and Schneider (1986) performed a multi-criteria evaluation that comprised of alternative transit system designs. The latter study used a computer-based multi-criteria approach with the use of concordance analysis to reveal how the best transit system design can recognized.

Keeney and Raiffa (1993) also focused on route planning and investigated the impacts of upfront context information on users' route selection. A number of studies have been developed assist in designing and evaluating sustainable transportation networks. To thoroughly analyze mass transit systems, all aspects (e.g., technical, environmental, economical, and social) should be involved (Tzeng et al., 1998; Saaty, 1995; Żak, 1999).

2.3.6 Pareto Optimal Frontier in Multi-modal Transportation

Planning multi-modal transportation to efficiently serve a population comes with a number of objectives, namely, cost, accessibility, environmental concerns, equity among the travelers, and revenue or profit. A number of criteria can be used to make a single selection within multi-modal transportation. Most of the factors that users usually focused on are the cost, time, and sometimes the benefits. Sometimes, there exists no single global solution when optimizing more than one objective. Hence, the Pareto frontier concept has been used to reach a set of points that can assist in fitting an encoded definition for an optimum. With the latter concept, the decision maker (DM) can meet the needs of operators, travelers, and other entities without compromising any constraints and preferences while selecting the most efficient points or

solutions. Yu (2013) and Kaiser and Miettinen (2001) divided Pareto optimal points into two categories, namely proper and improper. Researchers have also investigated when points are Pareto optimum (Brosowski and da Silva, 1994; Benson, 1978). When more than two objectives are presented, Pareto optimal is one of the concepts that is currently being used to solve the optimization by gaining its Pareto frontier. With the Pareto frontier curve or surface, users, transit agencies and stakeholders' decision making can be alleviated.

2.4 Chapter Summary

Section 2.1 of the literature review summarizes the sustainability concept and its development around the world. Since the growth of the sustainability adoption in the transportation field, several studies, more precisely a great number of dissertations, have investigated the sustainability concept. As this date, the sustainability concept is continuously an important topic around the world. Thinking of many goals each country has projected based on the sustainability concept, the author presumes that there will always be the need to practice and educate the new generation on said concept with the hope of making the concept more appealing to every nation. Yet, one of the main concerns of adopting the sustainability concept has been found to be the behavioral change of the users and their willingness to learn newer technologies. Section 2.2 focuses on studies that have evaluated public transportation network design and optimization.

All summarized articles in this study that have focused on optimizing public transportation have at least focused on one aspect of sustainability. Some of the articles analyzed only one mode of public transportation, while others explored multi-modal transportation and examined the same or different aspects/impacts. Nevertheless, the literature review has shown that not too many studies have focused on heavy rail transit, rapid rail transit, or subways, while the majority of the articles have focused

on urban buses of public transportation. A number of studies have investigated the environmental aspects of the sustainability concept, but most of those articles that fit under the environmental section have scrutinized emissions. While several articles analyzed emissions, only a few of them have taken into account the impacts of the driving operation modes of the studied modes of public transportation. Furthermore, it was observed that some studies used the same or different methodologies while optimizing the variables and ended up with slightly different conclusions. Other articles that developed different approaches while optimizing same variables have similar findings.

Reviewing different published articles that have focused on one of the three aspects of the sustainability concept, the author noted that not too many studies have focused on heavy rail transit. The majority of the studies that have investigated one of the sustainability aspects simply focus on the agency cost of operating and maintain heavy rail, using case studies of existing heavy rail systems. Based on the heavy rail mode of public transportation, more studies are needed to explore the emissions and the user cost of heavy rail transit. Another observation was that studies that evaluated the sustainability of the public transit area focused on the agency and user costs of operating one or more modes with the used of different or new approaches using the same or different constraints for the optimization.

CHAPTER 3

RESEARCH METHODOLOGY

This research was conducted in three steps, the first of which involved selecting different public transportation modes to be evaluated. The second step consisted of developing agency, user, and GHG emissions in terms of CO_2-equivalent equations to finalize a generalized cost for the evaluated public transportation modes. The final step involved selecting a number of different types of private cars that used different types of fuels and analyzing their emission rates, taking into account the different operation modes, namely, cruising, idling, and acceleration and deceleration, based on dynamic and static traffic network flow. The selection of the public transportation modes was not based on any criteria, but merely on the fact that they are some of the most currently operating modes around the world. Policy analysis and comparison using the general cost model were evaluated. To do so, a sensitivity analysis that involved several scenarios was conducted to assess the effects that demand, hourly user time cost, and cost of emissions have on a public transportation network system in a linear corridor. The results from these scenarios of the study could be used to help public transportation investors with their decision-making process when selecting a public transportation mode for a specific city.

The first part of this research approach targeted the economic aspect of the studied transit modes: the annual operating and maintenance costs, the capital cost, the user costs such as access time, waiting time, in-vehicle time saving, and transfer time costs. Other parameters, namely the yearly passenger miles traveled, the capacity of the vehicles, and the yearly ridership per route of the selected trunk technologies

above, were used to perform the analysis. Different typical resource variables such as vehicle-hours (VH), vehicle-distance (VD), and peak fleet size (FS) are very important to derive public transportation costs. Currently, comparison of bus rapid transit and light rail transit economic analyses are done by taking into account operations, maintenance, and capital costs. This study incorporates the concept of sustainability and the driving characteristics into the model to come up with the best decision in regard to choosing among local bus, full bus rapid transit, light rail transit, tram, and metro heavy rail modes. So, the model presents the facts and hypothesis based on the economic, environmental, and social impacts of each selected city in which these routes are operating to help decision makers.

The second part directed the users' impacts of choosing a transportation mode to reach their day to day destinations. User costs for this study include access time, the time for the users to get to the transit stops or station; the time wait for bus, light rail, or heavy rail to arrive, or simply the waiting time; the time in vehicle transit or the time from a transit stop to a final destination. For LRT, tram, full BRT, and MHR, this research assumes that other local trunk (e.g., feeder/local) technology is not involved in the trip to reach the transit line (i.e., transfer times between routes). Transfer times are denoted by , a constant per Daganzo (2010) that is different based on the coordination of the transit system. In this research, the transfer time is zero, and qualitative factors, such as the comfort of the ride and the pleasure or displeasure associated with traveling, are not included.

The third part can be broken into two sub-parts. The first sub-part evaluated the emissions factors within each mode of operations on a specific speed for each second of time using the vehicle specific power (VSP) for buses and the laws of physics conceptual were applied to model the rails emissions factors. The second aspect involved in converting the emissions factors into GHG emissions equivalent which later were quantified using a market price of GHG emissions per metric ton.

This research used an analytical methodology to optimize the capital, operating and maintenance (O & M) costs of the transit agency, the monetized total travel time, and the monetized cost of GHG emissions from studied transportation modes operating along a linear corridor. This research considers the frequency or the headway of the selected public transportation modes' service and the spacing of the stops as decision or design variables. Three models were developed to estimate the total system cost for each of the modes. The first model focuses on the operating and maintenance costs of the transit agency. The second model quantifies the users' total travel time cost. The third model evaluates the cost of CO_2-equivalent (CO_2e) from GHGs emitted by operating the buses.

Based on the definitions of the studied trunk technologies in this research, the total capital cost of each of these trunk technologies will be different. Capital cost of the local bus will be low, because this study made the assumptions that the bus will utilize existing infrastructure. LRT can be operated at a surface level over exclusive ROW or over public streets, and at the same time it can be granted exclusive right/graded separated ROW. Full BRT can use some of the existing infrastructure, but more capital cost is needed to operate full BRT in a city. Lastly, MHR, also known as rapid transit or subway, is most likely operating in the urban areas. It is obvious that MHR requires more capital cost, whether it is operating in a graded separated-in-tunnels ROW or on an elevated railway.

Let C_{tot}^{LB}, C_{tot}^{DBL} ,C_{tot}^{TRAM},C_{tot}^{BRT},C_{tot}^{LRT}, and C_{tot}^{MHR} represent the total capital cost for each of the six trunk technologies as indicated by the superscript: Regular buses (e.g., mixed-traffic and dedicated-lane), tram, LRT, full BRT, and MHR. Each mode cost (e.g., capital, O& M, users, and GHG) is reported individually and later combined into one general cost (GC) function to ease the optimization formulation. After combining the costs of all three E's, a generalized cost for each trunk of technology was developed. To quantify the environmental aspect among the three E's, another

model was developed using a modifying approach of the VSP method developed by (Frey et al., 2007) to quantify the cost of global warming potential of driving different cars with differing fuel propulsion. After optimization, a sensitivity analysis of several case scenarios was performed. Lastly, the generalized cost of each trunk technology was compared to one another by using various multi-criteria decision-making models (MCDMs), along with a number of assumptions, such as the population served by the line, the size of the city, ridership, and vehicle occupancy, to compare the lines, as well as several case scenarios and real-world case study.

Operating and maintenance costs for this research include fixed operating costs and variable operating costs (i.e., vehicle depreciation, fixed operating costs, driver salaries, administrative costs, insurance, fuel, spare parts, labor, repair, and maintenance). Annual operating and maintenance costs for each studied trunk technology were collected from (Chester, 2008).

Walking distance to transit stops or stations is hard to define, because it depends on where residents of possible transit-oriented developments (TODs) might work, shop, or prefer to go for services. Therefore, the walking distance to transit stops or stations might vary per passenger. Several previous studies found different results for walking distances to local transit stops, MHR and LRT stations(s), or BRT stops (Guerra et al., 2012; Dittmar and Ohland, 2012; Pushkarev and Zupan, 1975, 1977). Since the scope of this research is very broad, a constant speed within the accepted walking distance found in the guidelines used by North American companies was used to assume the walking distance to transit stops and stations for each trunk technology.

3.1 Assumptions and Limitations

As stated earlier in Chapter 1, this study used a continuous approximation approach using a number of assumptions for optimizing the overall general cost function for the PT modes and the selected private vehicles subject to different constraint such

as, the emission cost, the user cost, and the occupancy of the transit vehicle at every stop to be sure every passenger at a stop will be served. The assumptions that were made in this study can be summarized as the following:

1. The arrival demand rate was assumed to be fixed instead of elastic.

2. The size or the capacity of the vehicle technologies and the cost of the vehicles were also assumed to be constant values that were collected from previous findings. As if the latter were set to change based on the status of the economic and the location of the transportation system it could have made significant impacts.

3. This study considers a linear transit network and did not take into account the spatial structure of the location of the transportation system.

4. Because the emission factors the emission rates inputs that were collected from the VSP method of Zhai et al. (2008) and Frey et al. (2003) were used to calculate the emission factors for the bus and the full bus rapid transit, this study was limited to 45–48 kilometers per hour. Having that limitation, enable the author to explore the impacts of higher speeds, acceleration, and deceleration can have on the emission cost and the general cost of the technologies that used in mixed traffic or in its own dedicated lane or ROW and private vehicles.

5. Another disadvantage of the approach of this study is that it does not have the potential to handle uncertainty when choosing among the three aspects of the sustainability concept as well as real time information.

6. This study assumes that stop skipping public transit vehicles operating strategy is controlled to accommodate travelers with efficient transit services.

3.2 Static Traffic Network Model Formulation

One of tasks in the study included developing a generalized cost model, attaining real-world public transportation network data, conducting several scenarios of a sensitivity analysis, creating theoretical graph representations of these scenarios and comparing with different type of vehicles emissions to ease stakeholders' decision-making process when choosing among different public transportation modes in small and large size cities in a linear corridor using an analytical model that takes into account the different modes of driving operations and different features for both personal vehicles and public transportation.

Again, the goal of this analytical model was to develop an idealized public transportation routes operations system in a linear corridor whose characteristics, travel demand rate (λ), value of time per passenger (β), and value of emissions per gCO_2-e (γ) can be explored within the three aspects of the sustainability concept and compared with vehicle traffic emissions cost on the same network. A simple loop is considered for the analysis. The route is assumed to operate in a corridor of length $\frac{L}{2}$ in which λ passengers per hour per meter demand service. Each passenger walks to the nearest stop, waits for the next bus arrival, and travels an average distance of l.

The design of the system is characterized by the headway of service, H, and the spacing of stops, S, as shown in 3.1. Since the route must complete a loop in order for vehicles to return to service, the length of the route is L. Additional assumptions are that the road grade is flat ($r = 0$), and the public transit modes accelerate and decelerate at a constant rate of ± 1 meter per second squared. The configuration in 3.1 below is the same for all modes studied in this research.

3.3 User Travel Time Cost

The cost to users of riding the transit system is the time that it takes to complete a trip. The fare that is paid is not included in this calculation, because the fare is

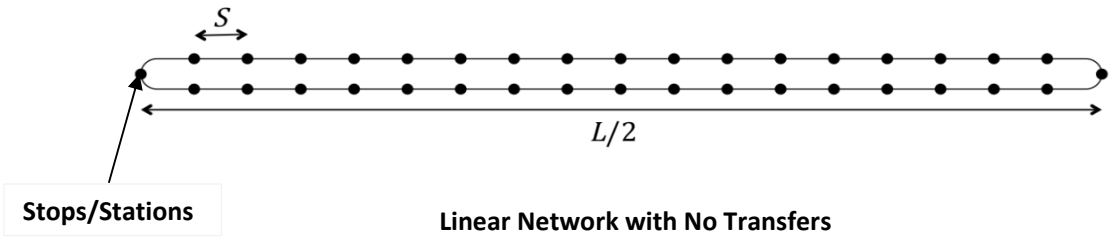


Figure 3.1. Linear Network with No Transfers.

a transfer from users to the agency, so it does not affect the total cost to society. The average travel time of riding public transit includes several steps, which can be identified as access time (t_a), waiting time (t_w), and in-vehicle time (t_{IVT}):

$$TT = t_a + t_w + t_{IVT} \tag{3.1}$$

The access time is that time is takes for the average passenger to walk to the nearest bus stop. This is assumed to be half of the stop spacing at an access speed of v_a. Therefore, the access time is

$$t_a = \frac{S}{2v_a} \tag{3.2}$$

The waiting time is, on average, a whole headway, if accounting for a trip made early enough that a passenger can be assured to reach an appointment at their destination on time:

$$t_w = H \tag{3.3}$$

Finally, the in-vehicle travel time is the length of the average trip, l, multiplied by the pace of the bus. The pace of the bus has three components. The first is the time

it takes to traverse distance at cruising speed, v_f. The second component is the time that is lost for acceleration and deceleration for each bus stop, t_s, multiplied by the number of stops per distance. The third is the time that buses spend dwelling per boarding and alighting passengers, tau_d, multiplied by the total number of passengers boarding and alighting per distance. The pace of the bus, which is the inverse of the average speed, is

$$\frac{1}{v_b} = \frac{1}{v_f} + \frac{\tau_s}{S} + \tau_d \lambda H. \tag{3.4}$$

As a result, the in-vehicle travel time is

$$t_{IVT} = l\left(\frac{1}{v_f} + \frac{\tau_s}{S} + \tau_d \lambda H\right). \tag{3.5}$$

Substituting expressions (3.2), (3.3), and (3.5) into (3.1), the travel time per passenger is:

$$TT_{bus} = \frac{S}{2v_a} + H + l\left(\frac{1}{v_f} + \frac{\tau_s}{S} + \tau_d \lambda H\right). \tag{3.6}$$

An important factor in determining the cost of travel time for users is to consider the equivalent value that passengers put on their time. Although the value of time is likely to vary from user to user, for the sake of analysis, it is useful to work with a single parameter β that represents the dollar value per hour of travel time that users' experience. This value of time allows making a trade-off between the different kinds of costs when optimizing the system design. The value of β is considered in the sensitivity analysis in Chapter 4.

3.4 Agency Cost of Service

The overall agency costs associated with operating and maintaining a bus route can be expressed as functions of three operational parameters: costs of stopping, costs

of traversing distance, and costs of operating time. The total agency cost per hour of system operation is given by

$$AC = c_s(N_s) + c_d(VMT) + c_t(VHT) \tag{3.7}$$

where c_s is the dollar cost per vehicle stop, c_d is the dollar cost per unit distance of vehicle operation, and c_t is the unit cost per unit time of vehicle operation. The costs of fuel, tires, driver and mechanic salaries, administration, etc. can all be broken down into components that are proportional to these aspects of the vehicle operations. For example, driver wages contribute substantially to the cost of time, because the driver must be paid whether the bus is moving or not. The cost of wear on the brakes is largely associated with the number of stops because the deceleration for vehicle stops has a large impact on brake use.

In order to estimate the total agency cost in equation (3.7), we need to model the operations of vehicles in the system. First, the number of vehicle miles traveled (VMT) must be considered. The cycle time for a vehicle to complete the entire route of length L is

$$C = \frac{L}{v_b} \tag{3.8}$$

where v_b is the average speed of the bus in service, including loss time and dwell time at stops. The total number of buses that are required to provide a service headway of H is:

$$M = \frac{C}{H}. \tag{3.9}$$

The total vehicle miles operated per hour of operation is then simply the total distance traveled by all M vehicles, which is $VMT = Mv_b$. By substituting (3.8) and (3.9) into this expression, the vehicle miles traveled can be calculated by

$$VMT = \frac{L}{H}. \tag{3.10}$$

Next, the number of vehicle stops in the system per hour of operation must be considered. This is simply the total distance traveled by all buses divided by the spacing of stops along that distance:

$$N_s = \frac{L}{SH}. \tag{3.11}$$

Finally, the total vehicle hours of operation must be considered. This can be calculated by dividing the VMT by the average speed of the buses, v_b. Substituting from (3.4), the expression for vehicle hours traveled is therefore

$$VHT = VMT\left(\frac{1}{v_f} + \frac{\tau_s}{S} + \tau_d \lambda H\right). \tag{3.12}$$

By substituting expressions (3.10), (3.11), and (3.12) into (3.8) and simplifying, the total agency cost can be expressed in terms of the decision variables as

$$AC = \frac{c_d L}{H} + \frac{c_s L}{SH} + \frac{c_t L}{vH} + \frac{c_t L \tau_s}{SH} + c_t L \tau_d \lambda H. \tag{3.13}$$

For comparison with the average user cost, it is necessary to consider the average agency cost per passenger, which is calculated by dividing (3.13) by λL, which is the hourly demand along the entire route:

$$\frac{AC_{MT}}{\lambda H} = \frac{c_d}{\lambda H} + \frac{c_s}{\lambda SH} + \frac{c_t}{\lambda v_{ops} H} + \frac{c_t \tau_s}{\lambda SH} + c_t \tau_d \tag{3.14}$$

$$\frac{AC_{ROW}}{\lambda H} = \frac{c_d}{\lambda H} + \frac{c_s}{\lambda SH} + \frac{c_t}{\lambda v_f H} + \frac{c_t \tau_s}{\lambda SH} + c_t \tau_d \tag{3.15}$$

where the agency cost for all trunk technologies that are operating in mixed traffic (MT) can be calculated using (3.14) while the transit modes operating in dedicated right-of-way as shown for the dedicated bus lane in Figure 3.2 below can be calculating using (3.15) .

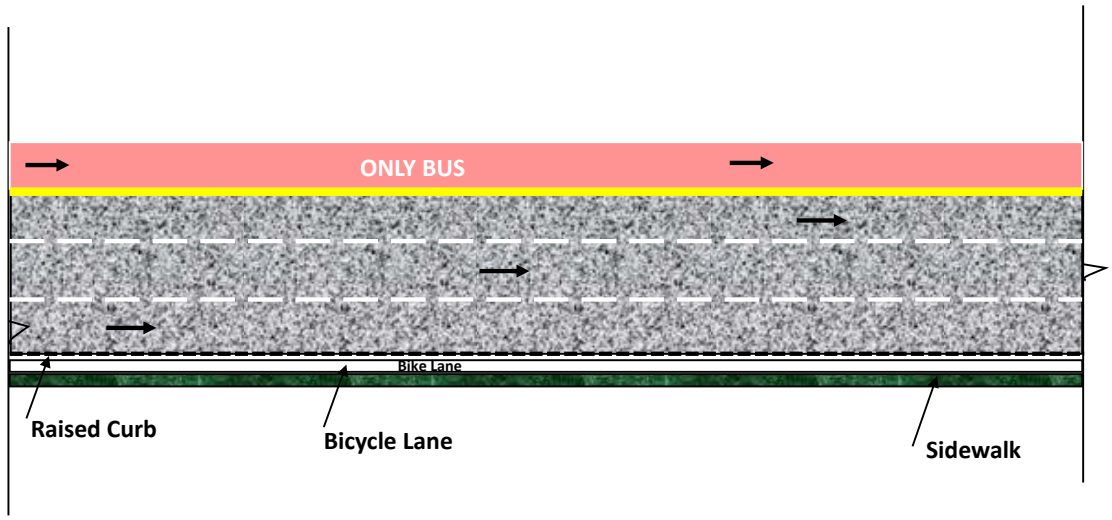


Figure 3.2. Schematic of a Dedicated Bus Lane (DBL)

Accounting for the capital cost of operating both mixed traffic and dedicated transit trunk technologies, equations (3.14) and (3.15) become the following with (3.16) for all modes operating in mixed traffic and (3.17) for the modes that operating in its own dedicated right of way.

$$\begin{aligned}\frac{AC_{MT}}{\lambda H} =& \frac{c_d}{\lambda H} + \frac{c_s}{\lambda SH} + \frac{c_t}{\lambda v_{ops} H} + \frac{c_t \tau_s}{\lambda SH} + c_t \tau_d \\ &+ \frac{c_{st}}{\lambda S} + \frac{c_v}{\lambda v_{ops} H} + \frac{c_v \tau_s}{\lambda SH} + c_v \tau_d + \frac{c_{inf}}{\lambda} \qquad (3.16)\\ \frac{AC_{ROW}}{\lambda H} =& \frac{c_d}{\lambda H} + \frac{c_s}{\lambda SH} + \frac{c_t}{\lambda v_f H} + \frac{c_t \tau_s}{\lambda SH} + c_t \tau_d \\ &+ \frac{c_s t}{\lambda S} + \frac{c_v}{\lambda v_f H} + \frac{c_v \tau_s}{\lambda SH} + c_v \tau_d + \frac{c_{inf}}{\lambda} \qquad (3.17)\end{aligned}$$

In equations (3.16) and (3.17), c_{st} is designated as the cost of stations, c_v is the cost of the fleet size, and c_{inf} represents the cost of infrastructure.

3.5 Diesel-Regular Buses Greenhouse Gases Emissions Modeling

Emissions of GHG and other pollutants, as well as the consumption of fuel, are related to the duration of acceleration, deceleration, cruising, and idling that a bus undergoes to traverse the route. This driving cycle is related to the cruising speed and the number of stops, including traffic lights, stop signs, and bus stops along a transit route. Changing components of the driving cycle can have a very large effect on the fuel consumption and emissions, based on simulation and experimental findings (Ozkan et al., 2012).

Emissions of greenhouse gases and other pollutants, as well as the consumption of fuel, are related to the duration of acceleration, deceleration, cruising and idling that a bus undergoes while traversing the route. Accounting for all driving operation modes, the emissions model presented in this dissertation takes into account the cost of pollutants emitted during cruising, idling, deceleration, and acceleration of the vehicle per hour in the system. Figure 3.3 shows how a detailed trajectory of a bus can be broken down into components of cruising, idling, deceleration, and acceleration. This driving cycle is related to the cruising speed and the number of times that the vehicle stops for traffic signals, stop signs, and bus stops along a transit route. The components are then associated with emission factors calculated using the VSP method in (Zhai et al., 2008; Frey et al., 2008, 2007). To estimate the emission factors of the different components of the driving cycle several steps were performed. This study considers a cruising speed of 12.5 $\frac{m}{s}$, idling buses are stationary (0 $\frac{m}{s}$), and acceleration and deceleration is at a constant rate of ± 1 m/s^2. The vehicle specific power (VSP) equation for transit buses was used developed in Andrei (2001) and used Zhai et al. (2008).

Equation (3.18) below was used to simply calculate the emission rates for all operating modes as shown in 3.3 for the regular buses and full bus rapid transit:

$$VSP = v\left(a + g\sin\left(\varphi\right) + 0.092\right) + 0.00021v^3 \tag{3.18}$$

where v is the vehicle speed expressed in units of m/s, a is the rate of acceleration in m/s^2, g is the acceleration of gravity, and φ is the angle of slope of the roadway (assumed to be 0 for the analysis in this dissertation).

After calculating the VSP values for the 6.25 seconds required to accelerate from 0 to 12.5 m/s, the VSP mode values from (Zhai et al., 2008) were used to estimate the values for each emission factor. Using the same method as (Zhai et al., 2008), each the VSP calculation for each second i of acceleration and deceleration was associated with a VSP bin, and each bin is associated with an emission rate resulting in a series of second by second emissions (E_i) in gCO_2/s. The definition of VSP bins and emission factors is summarized in Table 3.1. To obtain the total acceleration and deceleration emission factors, the following calculation was used using an Excel model:

$$EF_{\frac{acc}{dec}} = \sum_{i=1}^{7} E_i + \Delta t_i \tag{3.19}$$

where $EF_{\frac{acc}{dec}}$ is the corresponding emission quantity per acceleration event or deceleration event.

The model of emissions is based on estimates of the effective time spent cruising and the effective time spent idling using kinematic wave theory, which treats accelerations and decelerations as instantaneous events. Therefore, the emissions associated with the acceleration and deceleration corresponding to each vehicle stop must be expressed as the additional emission relative to the equivalent effect cruising and idling during the same duration of time. If acceleration and deceleration is at a constant rate, then half of the acceleration duration is effectively cruising and half is effectively idling. As a result the emission factor per stop (EF_s) is given by equation 3.20 below.

$$EF_s = EF_{acc} + EF_{dec} - \frac{t_{acc} + t_{dec}}{2}\left(EF_{cr} + EF_i\right) \tag{3.20}$$

These results are then converted into the 100-year global warming potential values to create a standardized measure of greenhouse gas emissions. Table 3.1 summarizes the emissions rates using the VSP approach assuming constant instantaneous acceleration and deceleration.

Table 3.1. VSP Modes and Associated Emissions of CO_2 for Diesel Buses Zhai et al. (2008)

VSP Range	VSP Mode (Bin)	Emission of gCO_2/s, E
VSP$\leq$ 0	1	2.4
0 < VSP< 2	2	7.8
2$\leq$ VSP< 4	3	12.5
4$\leq$ VSP< 6	4	17.1
6$\leq$ VSP< 8	5	21.2
8$\leq$ VSP< 10	6	24.8
10$\leq$ VSP< 13	7	27.6
VSP$\geq$ 13	8	29.5

The emission values are calculated and then converted into gCO_2e using the global warming potential (GWP) value for 100 years of each studied GHG pollutant as shown in Table 3.2. The estimated values for cruising and idling using the VSP mode approach were found to be 7.8 gCO_2/sec and 2.4 gCO_2/sec, corresponding to bins 1 and 2, respectively.

Table 3.2. GHG 100-Year Time Horizon Global Warming Potentials (GWP)

Greenhouse Gases	GWP_{100}	Chemical Formula
Nitrogen Oxides	8	NO_x
Carbon Dioxide	1	CO_2
Hydrocarbons	3	HC
Carbon Monoxide	3	CO

The calculations of these components are based on the same model elements that are used to estimate agency costs. When a public transit mode traverses distances, some of the time is spent cruising, some time is spent idling at stops, and some of the time is spent accelerating and decelerating. The emissions from cruising and

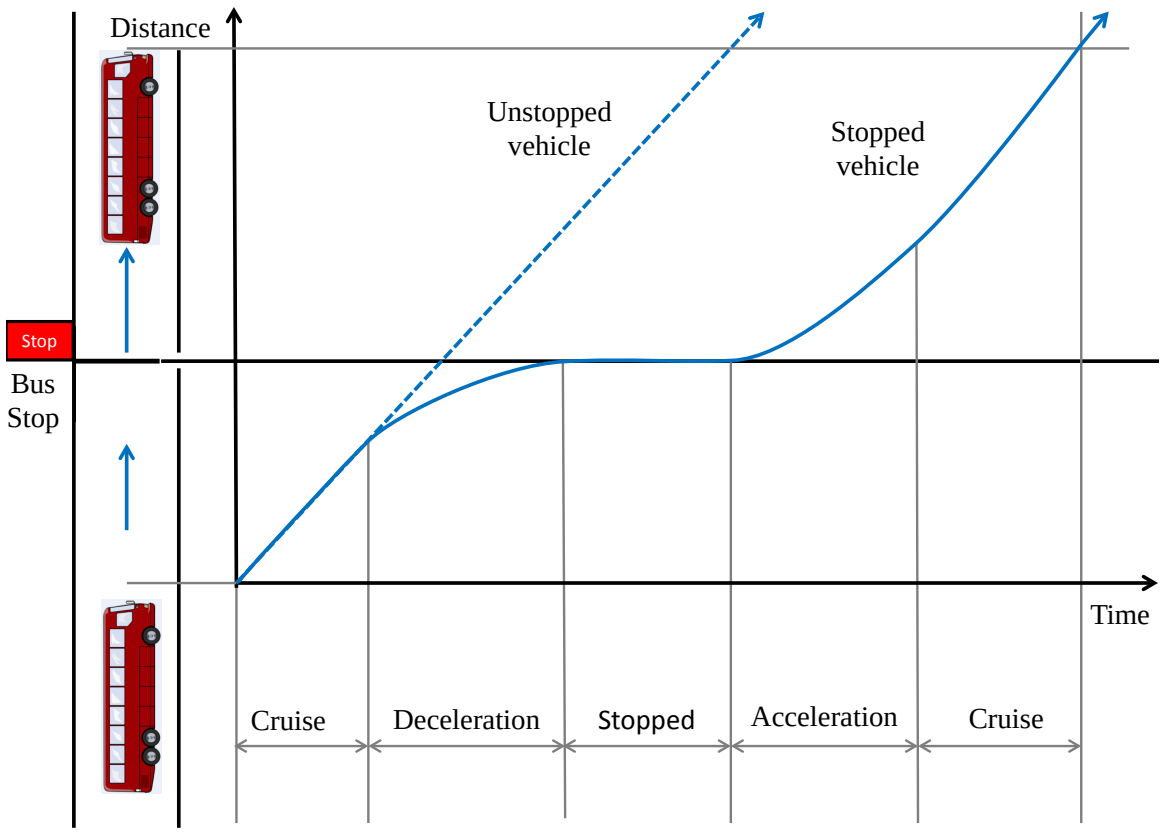


Figure 3.3. Vehicle Speed Profile Assuming Stops (Driving Cycle Components per Vehicle Miles Traveled).

idling are proportional to the time that bus spends in each of those driving modes. The emissions from acceleration and deceleration are associated with the trajectory of speed and acceleration that the bus experiences to make a stop. Therefore, the emissions from acceleration and deceleration can be combined into a single emission factor per stop.

To minimize the emission rate, the following equation was used:

$$E_r = EF_c T_c + EF_i T_i + EF_s N_s \tag{3.21}$$

where E_r is the emission rate, EF_c is the emission of greenhouse gas per vehicle cruising time, T_c is the cruising time, EF_i is the emissions per vehicle idling time, T_i is the idling time, EF_s is the emission from acceleration and deceleration per vehicle stop, and N_s is the number of vehicle stops per hour.

The total emissions associated with the operations of all public transit modes in the system are given by

$$E_{MT} = EF_c \frac{L}{Hv_f} + EF_i \left(\frac{L}{v_{ops}H} - \frac{L}{v_f H} + \tau_d L + \frac{L\tau_s}{SH} \right) + EF_s \left(\frac{L}{Hv_{ops}c_t} + \frac{L}{SH} \right) \tag{3.22}$$

$$E_{ROW} = EF_c \frac{L}{Hv_f} + EF_i \left(\frac{L\tau_s}{SH} \right) + \tau_d L + EF_s \left(\frac{L}{SH} \right) \tag{3.23}$$

where EF_c is the emission of GHG per vehicle cruising time, EF_i is the emissions per vehicle idling time, and EF_s is the emissions from acceleration and deceleration per vehicle stop. The corresponding components that are multiplied with these are cruising time (VMT/v_f), the idling time (the components of VMT/v_b when the vehicle is not moving), and the total number of stops (VMT/S). Again, it can be useful to present this expression in terms of the average emission per passenger, and this is calculated by dividing equations (3.22) and (3.23) by λL:

$$\begin{aligned} \frac{E_{MT}}{\lambda L} =& EF_c \frac{1}{\lambda H v_f} + EF_i \left(\frac{1}{\lambda v_{ops} H} - \frac{1}{v_f H} + \tau_d \lambda + \frac{\tau_s}{\lambda SH} \right) \\ &+ EF_s \left(\frac{1}{\lambda H v_{ops} c_t} + \frac{1}{\lambda SH} \right) \end{aligned} \tag{3.24}$$

$$\frac{E_{ROW}}{\lambda L} = EF_c \frac{1}{\lambda H v_f} + EF_i \left(\frac{\tau_s}{\lambda SH} + \tau_d \right) + EF_s \left(\frac{1}{\lambda SH} \right) \tag{3.25}$$

Finally, an important value for comparison with the user and agency costs is a monetary value per unit of GHG emitted. This value is denoted by , and it represents the dollar value associated with emission of CO_2e. There is not a consensus in the scientific community on what value should take. Some estimates quantify it as the

cost of social damage caused by the emission of the GHG. Other estimates are based on the cost of offsetting emissions with investments in alternative technologies. A range of values of $ 20 per ton CO_2e to more than $200 per metric ton CO_2e is reported by (Litterman, 2013). As some of the public transit modes in this research gain their energy from various alternative sources (e.g., coal, geothermal, hydrogen, offshore, and solar), their energy and emissions associated with capita for those modes will be further evaluated in the sensitivity analysis section in Chapter 4.

3.6 Rails Greenhouse Gases Emissions Modeling

Light rail transit is one of the transit modes that has been operated in urban transportation corridors around the world to assist travelers in reaching their destinations, as previously mentioned. This research focused on analyzing a single-track light rail transit, assuming a constant maximum operating speed. When planning to design an LRT route or system, it is always wise to primarily focus on the static parameters. More precisely, the static parameters that need to be evaluated are the train attributes (e.g., number of cars per train, motor power, length, and mass of train cars); the operational constraints, such as maximum operating speed and allowable travel time; the parameters of the vertical track profile (e.g., station spacing, vertical dip, and dip percentage); and the energy consumption and regeneration.

Over the past years, a number of studies around the world have previously explored train operational problems using several different analytical methodologies (Su et al., 2013; Kikuchi, 1991; Kim and Schonfeld, 1997; Yasunobu et al., 1984; Chang and Sim, 1997). Furthermore, Vuchic (1981) and Profillidis (2000) both tackled the electrodynamic braking of an LRT system. Based on Vuchic's and Profillidis's books, the kinetic energy that the power generated is released as heat in the air by the electric resistor; that same energy can also be regenerated to the power network.

The emissions model derived for optimizing the GWP emissions rates for the diesel local and dedicated buses in this research was not suitable for evaluating the emissions rates for LRT and MHR routes. One reason for the latter could be that the design of an LRT uses a much longer vertical curve, as well a smaller maximum grade, than does the design of a highway. Several researchers in the transportation engineering concentration have provided vertical alignment design guidelines to safely optimize and design rail transit and railroads (Wright and Ashford, 1989; Washington, 2001).

The emission models for light rail and metro in this study also applied the four driving operation modes when the train travels from station to station. The farther apart the stations are placed along the track, the more emission rates for the train increase. The performance of the train can be significantly affected, with frequent accelerations and decelerations when approaching and leaving each station.

The travel measures that can be affected by the latter can be noted as the tractive energy consumption and braking and the overall travel time of the passengers. The metro heavy rail, tram, and light rail transit emission models in this research start with the energy consumption assumptions and the mass of six-car train values that were provided in Vuchic (2007), Karlin et al. (1983), and Uher and Sharma (1986), respectively. Similar to Uher and Sharma (1986), both models assumed the typical energy that is required for 6-axle metro and light rail transit vehicles that run for 1 mile of distance, as shown in Figure 3.4.

The GHG emission rates produced by metro and light rail during each of the driving cycle modes were evaluated using elementary physics formulae for the auxiliary mode. First, the energy consumption when a train is operating during a specific time in the cruising, idling, acceleration, and deceleration modes was calculated. To calculate the energy consumption within the acceleration and deceleration modes, the traction effort (TE) and average total resistance (R_{avg}) acting on the vehicle when moving were calculated, using the following equations that are found in (Vuchic,

2007), considering the acceleration and deceleration as a function of speed and time:

$$TE - R_{avg} = m\frac{dv}{dt} \tag{3.26}$$

with TE and R_{avg} in newton (N), and the mass (m) in kilograms (kg), the acceleration ($a = \frac{dv}{dt}$) in m/s^2, the speed v in meter per second (m/sec), and the time t in seconds(s).

Assuming the vehicle moves a constant speed, $\frac{dv}{dt} = 0$, that implies that the above equation becomes

$$TE = R_{avg} \tag{3.27}$$

The average resistance (R_{avg}) was calculated as shown in the following equation in (Vuchic, 2007):

$$R^r = \left(0.65 + \frac{129}{p} + 0.009V\right) G + 0.0716V_r^2 \tag{3.28}$$

with R as resistance in Newton, r indicating rail, p as the axle loading in KN, V as the speed in Km/hr, and G as the vehicle weight in KN.

Figure 3.4 shows the different modes of a metro heavy rail, tram, and light rail transit from one station to the next station. Figure 3.4 also shows the different types of energies that are produced. Since this study only focuses on the GHG emission cost and the other two aspects of the sustainability concept, the tram,light rail, and metro heavy rail emission models only focus on calculating the emission rates within all four driving cycles, without taking into account the efficiency of the train engine. Nevertheless, the energy lost due to friction and the energy put out by the engine were taken into consideration in the calculations. The efficiency percentage loss that was used in this calculation was found to be within the range that was mentioned in (Vuchic, 2007). For the purpose of this emissions model, the kinetic energy (KE) is

the only energy that matters when the train is in the auxiliary mode from stations to station along the route.

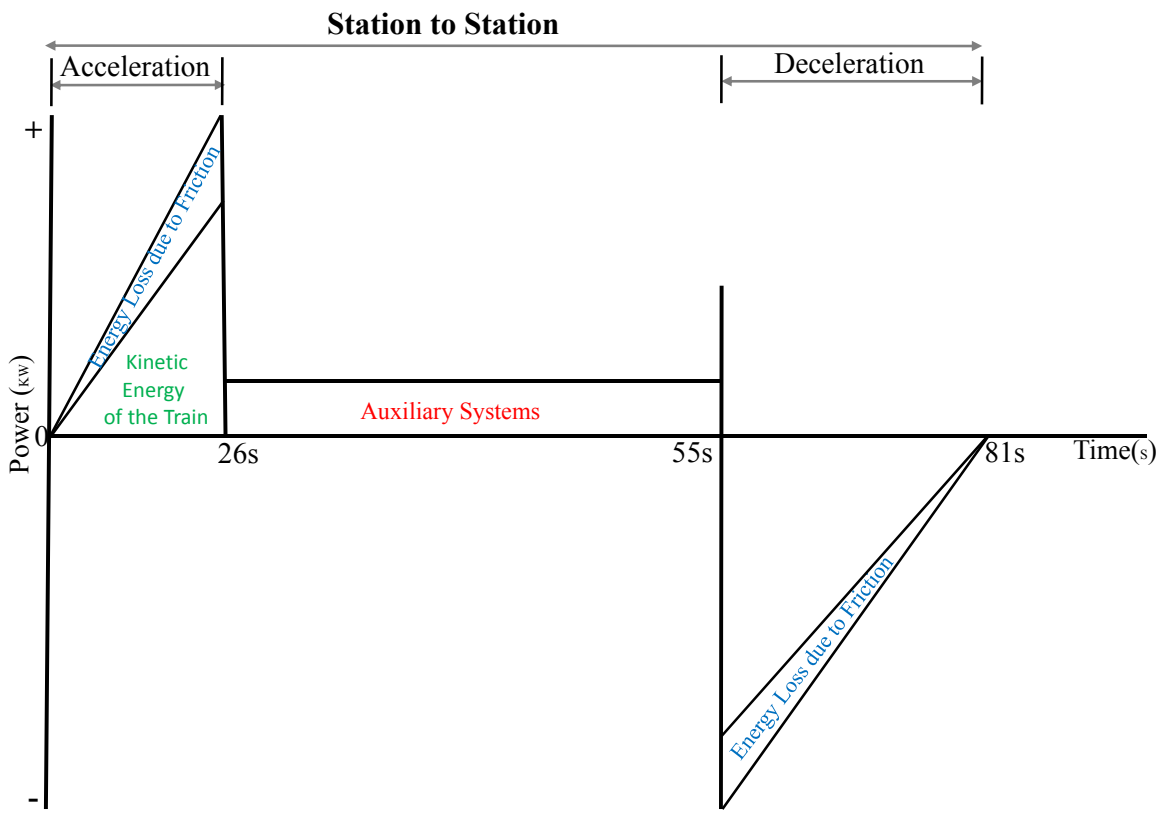


Figure 3.4. Rail Vehicle Speed Profile Assuming Stops.

Therefore, assuming a constant speed, the velocity of the train has the following interval in equations (3.29) and (3.29).

$$v_{Rail} \geq 0 \tag{3.29}$$

When the train is accelerating and decelerating, its corresponding velocity for accelerating and decelerating is shown in equation (3.29), and whenever the train stops, its velocity reaches zero.

$$\pm 0 \leq v_{LRT} \leq v_f \tag{3.30}$$

Based on the driving cycle that is shown above in Figure 3.4, the energy consumption is a quadratic function, while the power is a linear function so the assumption can be made to have a constant force. The derivation of the energy in each mode can be expressed as the following. Thus, the KE can be calculated by integrating the power in terms of time as shown in in equations (3.31) through (3.32).

$$P = \frac{dE}{dt} \tag{3.31}$$

Based on the power equation above, the energy can be derived as follows:

$$E = \int P dt \tag{3.32}$$

The kinetic energy of the train can be calculated using equation (3.33)

$$KE = \frac{1}{2} m v_{Rail}^2 \tag{3.33}$$

where E, P, KE, v, m, and t in equations (3.31) and (3.33) denote the energy, power, kinetic energy, velocity, the mass of the train, and time. When the train is running in the auxiliary section of the profile, the coasting emission rate can be calculated in the auxiliary mode using the constant free-flow speed. Lastly, when the train is approaching the next station, the deceleration emission rate can be calculated using the braking energy.

The emission factors that were found using the VSP method and the resistance motion and kinetic energy formulations to estimate the amount of pollutants released into the atmosphere for a 48-foot diesel bus and a 64-foot articulated full bus rapid transit vehicle, light rail, and metro heavy rail respectively are summarized in Figure 3.5. Tables A.15, A.16, A.17, and A.18 in Appendix A show the findings for 20 percent sensitivity results of rails and Full bus rapid transit GHG emissions.

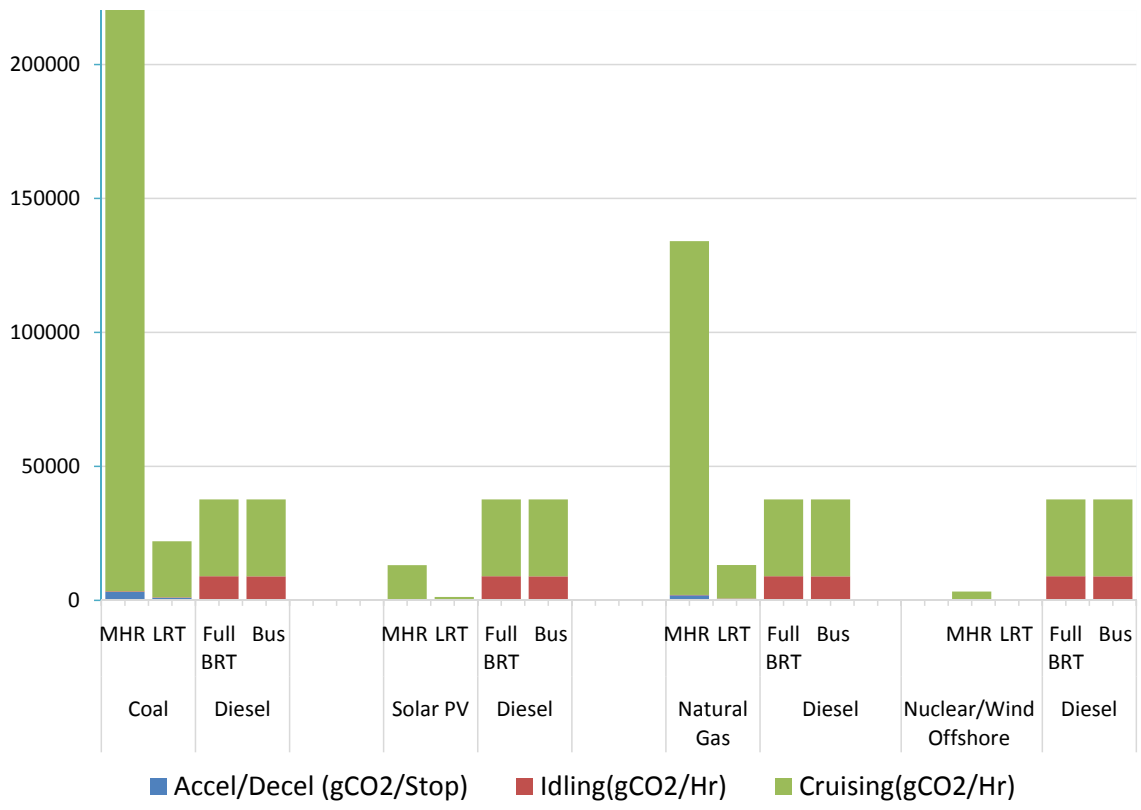


Figure 3.5. Transit Technology Driving Cycle Components Emissions.

Table 3.5 shows the calculated transit emissions when each trunk technology is operating in different driving cycle mode and also when their power sources are obtained from different sources. It can be noticed that the idling emissions factor for rails was found to be the same, based on the author's assumption that tram, light rail, and metro rail use the same amount of energy during the idling phase. A comment that be drawn from the results of the emissions factors in table 3.5 in Appendix A is that when rails are operated by coal, the cruising and acceleration/deceleration emissions were found to be the highest, while the emissions factors when rails are gaining energy from a nuclear or a wind offshore source were found to be the lowest.

After calculating the emission rates in each cycle for both metro rail and light rail, the GWP values in table 3.2 for each of the direct and indirect GHG were used

to convert into gCO_2e before using these emission rates into the emission equations that were described above in section 3.5.

Table 3.2 shows the global warming potential factors that were found from several different sources (e.g., EPA) and used in the emissions model section to calculate emissions rates to optimize the general cost function. This study has only focused on the most significant pollutants that affect the environment. Hence, only the GWP value was used to convert the emission factors for all technologies that were investigated in this research.

3.7 Generalized Cost Function for Public Transportation

With models for the user cost, agency cost, and emissions cost presented in the previous sections, these can be combined into a single generalized cost function. When expressed as a cost per passenger, the generalized cost is a function of both decision variables,

$$Z(S,H) = \beta(TT) + \frac{AC}{\lambda L} + \gamma\left(\frac{E}{\lambda L}\right). \tag{3.34}$$

which can be expressed explicitly by substituting in the right-hand sides of equations (3.6), (3.13), and (3.23). The first order conditions can be used to solve for the optimal headway as a function of the stop spacing:

$$H^*(S) = \sqrt{\frac{c_d + \frac{c_s}{S} + \frac{c_t}{v_f} + \frac{c_t\tau_s}{S} + \gamma\left(\frac{EF_c}{v_f} + \frac{EF_i\tau_s}{S} + \frac{EF_s}{S}\right)}{\beta\left(\lambda + l\tau_d\lambda^2\right)}}. \tag{3.35}$$

Alternatively, the first order conditions can be used to solve for the optimal stop spacing as a function of headway:

$$S^*(H) = \sqrt{\frac{2v_a}{\beta}(\tau_s l\beta + \frac{c_s}{\lambda H} + \frac{c_t\tau_s}{H} + \frac{EF_i\tau_s}{H} + \frac{EF_s}{H}}. \tag{3.36}$$

Either of these optimized values can be substituted back into equation (3.16) to express the generalized cost in terms of a single decision variable, z(S) or z(H). This can be used to identify the optimal design quickly.

An express bus with only dedicated ROW with different stop spacing along the same linear transit corridor is also operating with different headway. The same equations above are used to optimize the express bus, with some changes (e.g., transit signal priority, free-flow speed) that characterize express buses.

This research also considers a Light rail transit, tram, full bus rapid transit, and metro heavy rail routes with a uniform travel demand rate following a many-to-many travel pattern. The design of these public transit modes in this study have been evaluated in isolation. To better accommodate accessibility to travelers, the study assumes that stations or stops are placed within walking distance or travelers are biking or driving their private vehicles to the Park-and-Ride/Kiss-and-Ride (or incentive parking). Therefore, users are not experiencing additional time to transfer when completing their trip.

The equation to evaluate the overall travel time per passenger of light rail transit, full BRT, tram, and metro heavy rail routes in a linear corridor is somewhat similar to the travel time per passenger when using a local bus in the same transit network structure analyzed in Section 3.1. However, light rail travel time per passenger is more likely to be longer, depending on the transit headway, the density of the city, the length and speed of the route, the number of stops along the route, and the additional transfer time. To summarize, the same equations in Section 3.1 have been used to analyze all public transit modes in this study. However, the variables are more likely to vary for each mode.

3.7.1 Methodology Definition of Modes and Terms

For the purpose of this research, the agency cost of the public transit routes includes the total capital cost (C_{cap})in addition to the three operational costs, namely cost of stopping, cost of traversing distance, and cost of operating time. The capital cost of the modes includes one-time fixed cost and variable cost to the infrastructure and equipment cost and fleet size, respectively, of the route. These operation costs have been collected from previous studies where the life-cycle and the amortized cost of the public transit modes were taken into account. So, this study assumes that each selected trunk technology intends to pay back the capital cost based on a number of years. Since the analysis in this study only focused on some specific individual routes, the capital cost was divided by the route length in meters. So, the capital cost C_{cap} is the cost of land for the ROW and the construction of infrastructure in that ROW, and L is the length of the route in meters, and W is the width of the ROW in meters. Hence, the capital cost is analyzed separately by equation (3.37) before adding it to the cost model. The reason for analyzing the capital cost separately is in order to evaluate if the increased capital cost can be recovered. Hence, the total agency cost of the studied route is the following:

$$AC = (I_c + C_l)\text{Area} + C_v(\text{Fleet Size}) + C_s(\text{Stops}) + C_d(VMT) + C_t(VHT) + C_{stat}. \tag{3.37}$$

In equation (3.37), I_c is the cost of infrastructure, and C_l is the ROW cost or the cost of land. Furthermore, C_v is the amortized capital cost of purchasing the transit vehicles, C_{stat} is the capital cost of building the stations.

The infrastructure cost is multiplied by the area of the pavement and ROW as the following:

$$C_i(Area) = (I_c + C_l)LW. \tag{3.38}$$

where C_i is the initial capital cost. The variable cost in equation (3.37) is calculated based on the following:

$$C_v = (\frac{L}{Hv_f} + \frac{L\tau_{accel/dec}}{SH} + \tau_d \lambda H. \tag{3.39}$$

The total agency cost is divided by λ L to obtain the cost per passenger. Then, the agency cost to operate an LRT, a full BRT, and an MHR route is as follows:

$$\frac{AC}{\lambda H} = \frac{c_d}{\lambda H} + \frac{c_s \tau_s}{\lambda SH} + \frac{c_t}{\lambda v_f H} + \frac{c_t \tau_s}{\lambda SH} + c_t \tau_d + \frac{c_i LW}{\lambda L} + \frac{c_v}{\lambda H v_f} + c_v \tau_d + \frac{c_v \tau_{accel/dec}}{\lambda SH} + \frac{c_{stat}}{\lambda SH}. \tag{3.40}$$

3.8 Light Duty Private Automobiles Model

The second aspect of this research is quantifying the GHG emissions of different types of cars with different fuel propulsion. The VSP method incorporates driving characteristics (e.g., cruising, idling, and acceleration/deceleration). The following VSP equation that was used in (Frey et al., 2002; Zhai et al., 2008) was used to calculate the emissions factors for the two vehicles (e.g., Prius II and Chevy Cavalier) that were evaluated. Table 3.3 was used to evaluate the emissions factors for both cars.

$$VSP = v\,(1.1a + g\sin(a\tan(r)) + 0.132) + 0.000302v^3 \tag{3.41}$$

Additionally, an assumption of having a static traffic network was made. Two vehicles were added into the existing network with the local and the dedicated lane buses, full BRT the tram, LRT, and MHR. Using the same VSP approach, the GHG emissions for five private vehicles were calculated, using the same model that was used for the buses:

$$E_{cars} = \frac{lEF_c}{v_f} + l\left(\frac{EF_i}{v_f} - \frac{EF_i}{v_f}\right) + \frac{lEF_s}{c_t v_f v_{ops}}. \tag{3.42}$$

Table 3.3. VSP Bin and Associated Emissions of CO_2 for Hybrid Vehicles Wu et al. (2015)

VSP Range(kW/t)	Vehicle Speed(km/h)				
		$v \leq 1.6$	$1.6 < v \leq 40$	$40 < v \leq 80$	$v > 80$
VSP≤-4	Bin 0	Bin 1	Bin 11	Bin 21	Bin 35
-4 <VSP< -2	Deceleration	Idling	Bin 12	Bin 22	
-2≤ VSP< 0			Bin 13	Bin 23	
0≤ VSP< 2			Bin 14	Bin 24	
2≤ VSP< 4			Bin 15	Bin 25	
4≤ VSP< 6			Bin 16	Bin 26	Bin 36
6≤ VSP< 8			Bin 17	Bin 27	Bin 37
VSP≥ 8			Bin 18	Bin 28	Bin 38

The emissions cost per passenger was calculated using the market price of the emission of CO_2e by multiplying equation (3.42) by γ.

$$\gamma E_{cars} = \gamma \left(\frac{lEF_c}{v_f} + \frac{lEF_i}{v_f} - \frac{lEF_i}{v_f} - \frac{lEF_s}{c_l v_c} \right). \tag{3.43}$$

$$= \gamma \frac{lEF_c}{v_f} + \gamma l \left(\frac{EF_i}{v_f} - \frac{EF_i}{v_f} \right) + \gamma \frac{lEF_s}{c_t v_f v_{ops}}. \tag{3.44}$$

3.8.1 Light Duty Private Automobiles User Costs

Similar to the public transit modes, the overall travel cost of using a private vehicle was calculated as the following:

$$TT_{cars} = \beta \left(\frac{l}{v_{ops}} + v_a \right). \tag{3.45}$$

3.8.2 Light Duty Private Automobiles Ownership Cost

The overall operating cost of owning a private vehicle is equal the following:

$$Ops_{cars} = \frac{lc_t}{v_{ops}} + lc_d. \tag{3.46}$$

In equations (3.31), (3.43), (3.44), (3.45), and (3.46), E_{Car} represents the overall emissions per vehicle, with v_{ops} as the operation or commercial speed.

3.8.3 Light Duty Private Vehicles Greenhouse Gas Emissions

The VSP method incorporates driving characteristics (e.g., cruising, idling, acceleration, and deceleration). Additionally, an assumption of having a static traffic network was made. Five vehicles were added into the existing network with the local and the dedicated lane buses, the full BRT, tram, ant the rails, but only two vehicles were used to reach the findings in this dissertation. Using the same VSP approach, the GHG emission for five private vehicles were calculated using the same model that was used for the buses.

The emission cost per passenger was calculated using the market price of the emission of CO_2-equivalent by multiplying equation (3.42) by γ.

In equations (3.45), (3.46), (3.42), (3.43), and (3.44), E_{cars} represents the overall emissions per vehicle, with v_ops as the average operating speed in traffic.

3.8.4 Light Duty Private Automobiles Generalized Cost Function

To calculate the generalized cost of the private vehicles, the owner total operating cost of a vehicle per mile was multiplied for the average length of trip. The owner operating cost of the automobile from (Gonzales, 2011) was used. Private vehicle user cost, owner operating cost, and emissions cost were added to come up with the generalized cost of a private vehicle per passenger.

$$Z_{cars} = \gamma E_{cars} + TT_{cars} + Ops_{cars} \tag{3.47}$$

3.8.5 Trunk Technology Generalized Cost Function Optimization

To thoroughly investigate emissions on the generalized cost of sustainable multimodal transportation, the following optimizations were conducted for each trunk technology in this study when the optimizations were formulated differently.

Equation (3.48) optimized generalized cost subject to the occupancy of the mode. As travelers' mode of choice changes every single day based on multi-criteria decision-

making process, in equation (3.49) the GHG emissions of the modes were optimized subject to the generalized cost less than or equal to the private vehicle cost to take into consideration the multi-criteria decision making of travelers with stop spacing(S), headway(H), and technology as decision variables. Each optimization was set up to automatically calculate the optimum capacity of the vehicle to avoid having passengers waiting at each stop or station.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & Z(S,H) \\ \text{subject to} \quad & S,H \geq 0 \end{aligned} \tag{3.48}$$

With the involvement of real data information to assist travelers in making better decisions when adopting or switching to a better mode, looking at the effects of travelers switching to more suitable modes to reach their destinations is important. This study also looked a number of optimizations that capture the human behavior of travelers without uncertainty. Therefore, the GHG emissions cost was also optimized to see the difference when travelers switch to a different mode of transportation to improve their travel time:

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & E(S,H) \\ \text{subject to} \quad & S,H \geq 0 \\ & Z(S,H)_{Transit} \geq Z(S,H)_{Car} \end{aligned} \tag{3.49}$$

In addition to the two preceding optimizations, two other optimization formulae were developed to investigate the GHG emission costs that were found to be very small compared to the other two costs (user and agency costs) that were part of the general cost composed based on the three E's of sustainability to simultaneously optimize all three aspects. Equations (3.50) and (3.51) below show those two optimizations formulations.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & (\beta(UC) + AC) \\ \text{subject to} \quad & S, H \geq 0 \\ & \text{GHG Emissions Cost} \leq E_k \end{aligned} \tag{3.50}$$

Next, the GHG emissions cost was used as the function to be minimized, using the total cost composed of the summation of user cost and agency cost as shown in equation 3.51.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & (\text{GHG Emissions}) \\ \text{subject to} \quad & S, H \geq 0 \\ & (\beta(UC) + AC) \end{aligned} \tag{3.51}$$

Furthermore, this study performed an analysis to investigate the Pareto frontier based on some characteristics of the technologies that were investigated. The Pareto frontier has been used to identify trade-offs in previous multi-criteria multimodal transportation studies (Marler and Arora, 2004; Hochmair, 2008; Bai et al., 2011; Wu et al., 2012; Das et al., 2012; Sun and Lang, 2015; Brands and Berkum, 2014), which is summarized later in the multi-criteria analysis section in this dissertation. The Pareto-frontier analysis was conducted to show the technology or technologies that suit a city in terms of demand rate, value of time, length of route, and other criteria. The optimization function was formulated as shown in equation 3.51 or 3.52.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & (\beta(UC) + AC) \\ \text{subject to} \quad & S, H \geq 0 \\ & \text{GHG Emissions} \leq E_k \end{aligned} \tag{3.52}$$

In this study, E_k the minimum possible constant for the emission value was chosen, and then a range of values between 0 and 1 were used to plug the objective function in the optimization in equation (3.52). Either equation (3.51) or equation (3.52) could have been used as both optimizations to answer the same question.

3.9 Chapter Summary

Chapter 3 explains in detail the steps in the overall methodology of this research, including the optimization functions that were conducted to obtain the findings. In this chapter, different optimizations were performed to assist in answering the research questions as well as to explore the policy questions that might of interest to policy makers, stakeholders, and transit agencies. With the findings from the optimization, several sensitivity case scenarios were conducted to look at the impact of variables of the general cost for each aspect of the sustainability concept. The following Chapter 4 contains the contour graphs and the sensitivity analysis that was performed to interpret the findings of this study.

CHAPTER 4

GENERALIZED COST FUNCTION

This section of the report focuses on analyzing how the generalized cost is impacted when the values of the variables are changed. Section 4.1 focuses on the decision variable that is the most sensitive to the generalized cost. The latter section also investigates how the generalized cost changes when the decision variables increase or decrease. Section 4.2 focuses on the optimization program of evaluating the three aspects of the sustainability concept when operating a local or dedicated bus lane in an urban area. Sections 4.3.2, 4.3.3, and 4.3.4 focus on interpreting and insight on the findings of operating a full BRT, an LRT, and an MHR based on the three aspects of the sustainability concept.

4.1 Diesel Regular Bus Design Variables Effects on Generalized Cost

To explore the effects of the optimal design on the generalized cost of a mixed-traffic bus and a dedicated bus, two contour graphs were plotted in Matlab. Figures 4.1 and 4.2 show that the generalized cost is impacted by the stop spacing and headways. The shape of the contours shows that the generalized cost is more sensitive to headway than to stop spacing. Figures 4.1 and 4.2 show the effects of the mixed traffic bus and DBL design variables on the generalized cost.

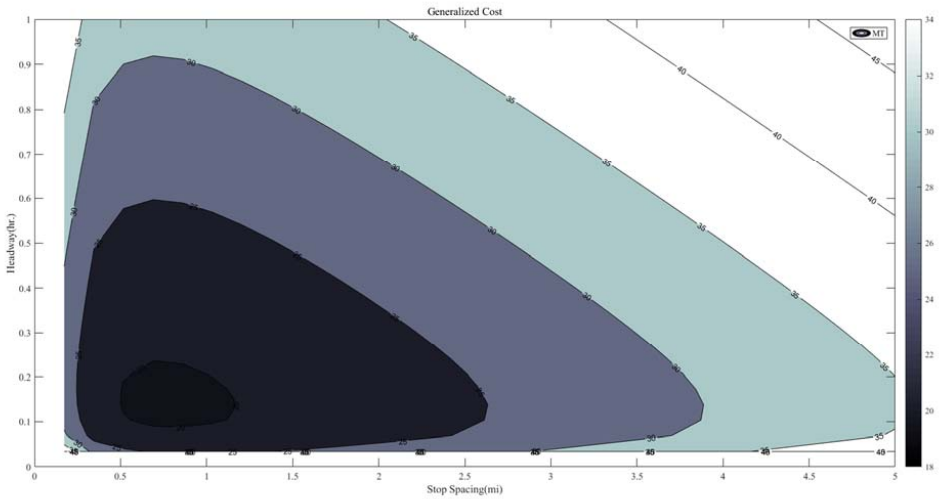


Figure 4.1. Mixed Traffic Bus Generalized Cost Effect(s) on Stop Spacing and Headway.

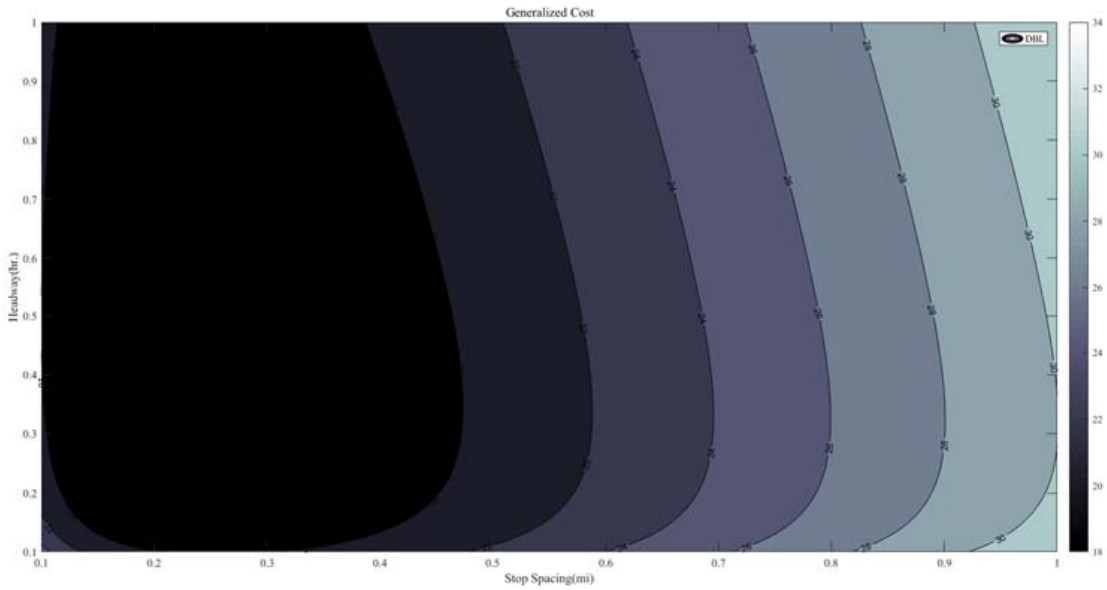


Figure 4.2. DBL Generalized Cost Effects on Stop Spacing and Headway.

4.2 Full Bus Rapid Transit Design Variables Effects on Generalized Cost

Similar to the analyses that were conducted to evaluate the DBL and the mixed-traffic (MT) mode, a contour graph 4.3 evaluating the impacts of the headway and stop spacing on the generalized was also constructed, assuming a demand rate of five trips per mile-hour and a value of time of $20 per hour. It was found that when headway and stop spacing were diminished or increased, so did the generalized cost. The optimal point was found within the generalized cost values that are in the smallest circle. Additionally, it was found that the headway had more significant effect on the generalized cost. It can be interpreted that transit agencies need to rely more on the headway of a transit mode if all three aspects of the sustainability concept are taken into account.

The same theory in regards to the generalized cost effects of full BRT as that of the DBL and mixed-traffic bus was found. This means that the generalized cost of full BRT was affected by S or H. However, a full BRT appears to be the choice able to carry the most passengers quickly with a higher number of passengers on each vehicle.

The full BRT mode was also evaluated against the rail modes in this study. Graphs that evaluated the generalized per dollars, GHG emissions cost, and emissions per gCO_2e among the full BRT, tram, LRT, and MHR were also plotted for interpreting the findings in regard to full BRT. The takeaway from those graphs was that a full BRT is competitive with a DBL at some specific level of demand. In terms of sustainability in general, a full BRT was found to be the next suitable mode after a DBL.

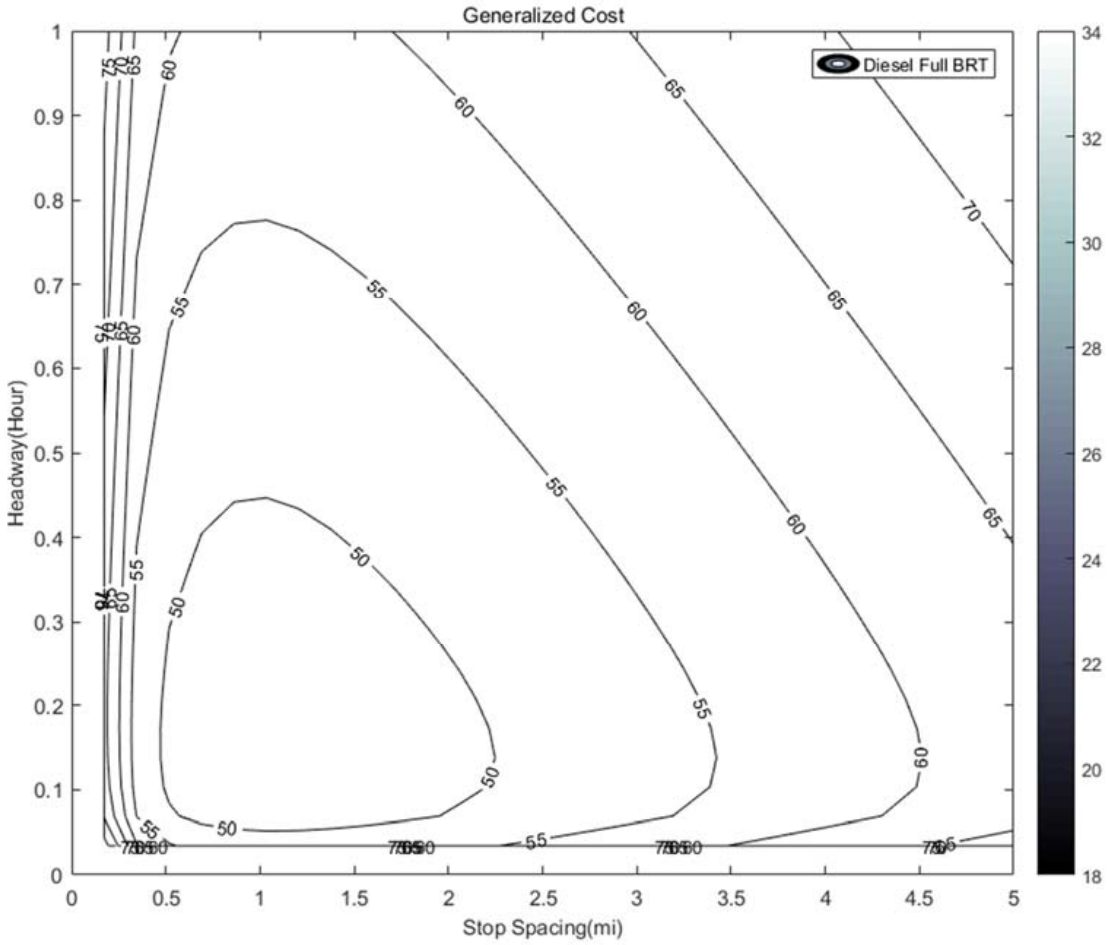


Figure 4.3. Effects of Decision Variables (S, H) on GC of Full BRT.

4.3 Tram and Light Rail Design Variables on the Generalized Cost

A light rail transit mode is world renown as a technology that not only has the potential to transport a large number of travelers in a wide range of cities, but also as the mode that produces less emissions than the other transportation modes, with the benefits of reducing air pollution, energy consumption, and GHG emissions.

To investigate the sustainable potential of an LRT route in this research, a number of analyses were performed. Similar to the other modes, contour graphs were plotted for different demand rates and values of time to explore the impacts on the generalized

cost. LRT was also plotted with all other technologies to evaluate different factors that transit agencies or travelers consider when making decisions to plan or adapt a technology. Tables A.12 and A.13 in Appendix A summarize the tipping points of all transportation modes when fuels other than coal have been used.

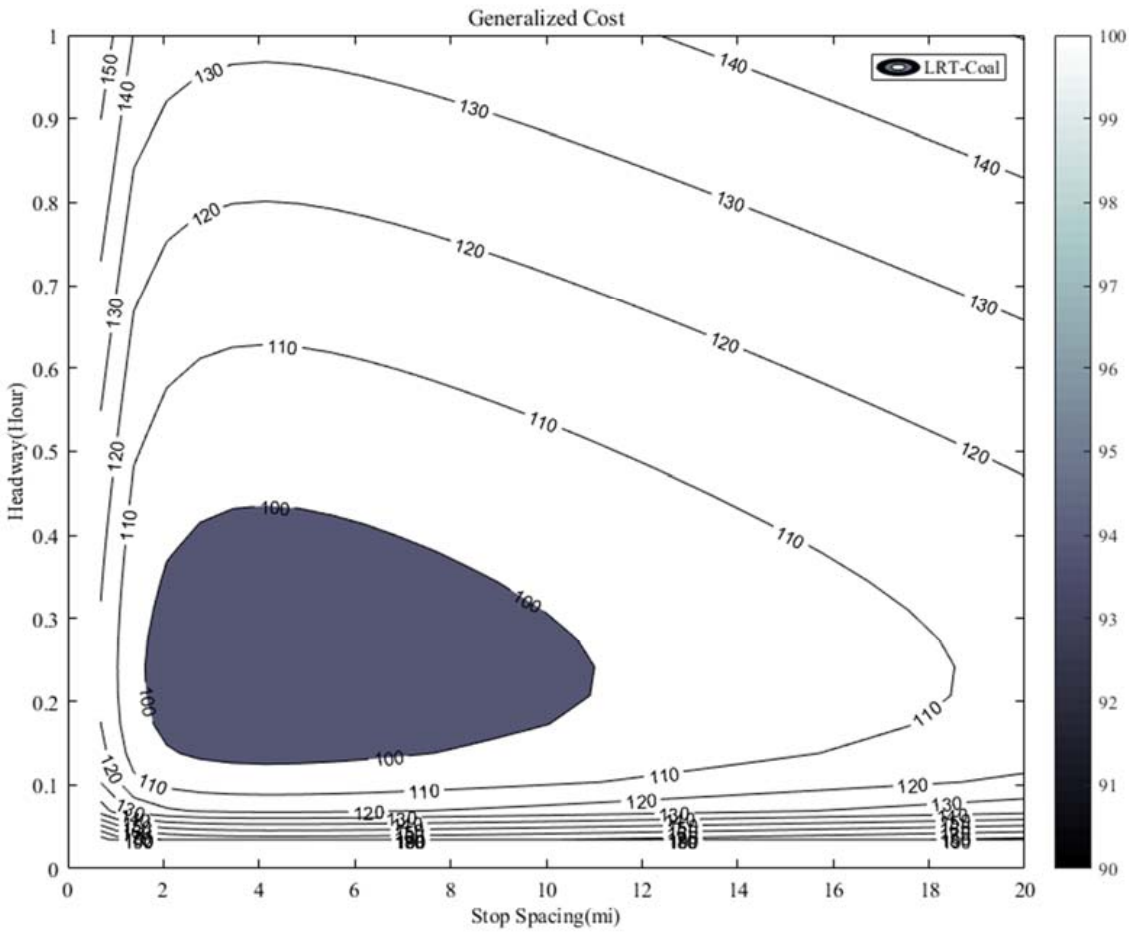


Figure 4.4. Effect of Light Rail Transit GC as a Function of Decision Variables.

Sensitivity analyses were also performed to show the input variables that were the most affected when LRT gained energy from different types of power plants. Pareto frontier plots were created to investigate the sustainability aspects that were affected when LRT technology was being operated in a city. In this research, LRT and tram were first compared in terms of CO_2e emissions when rails used their energy from

different power plants. The findings indicated that when the demand is very low, a tram is competitive with a LRT route.

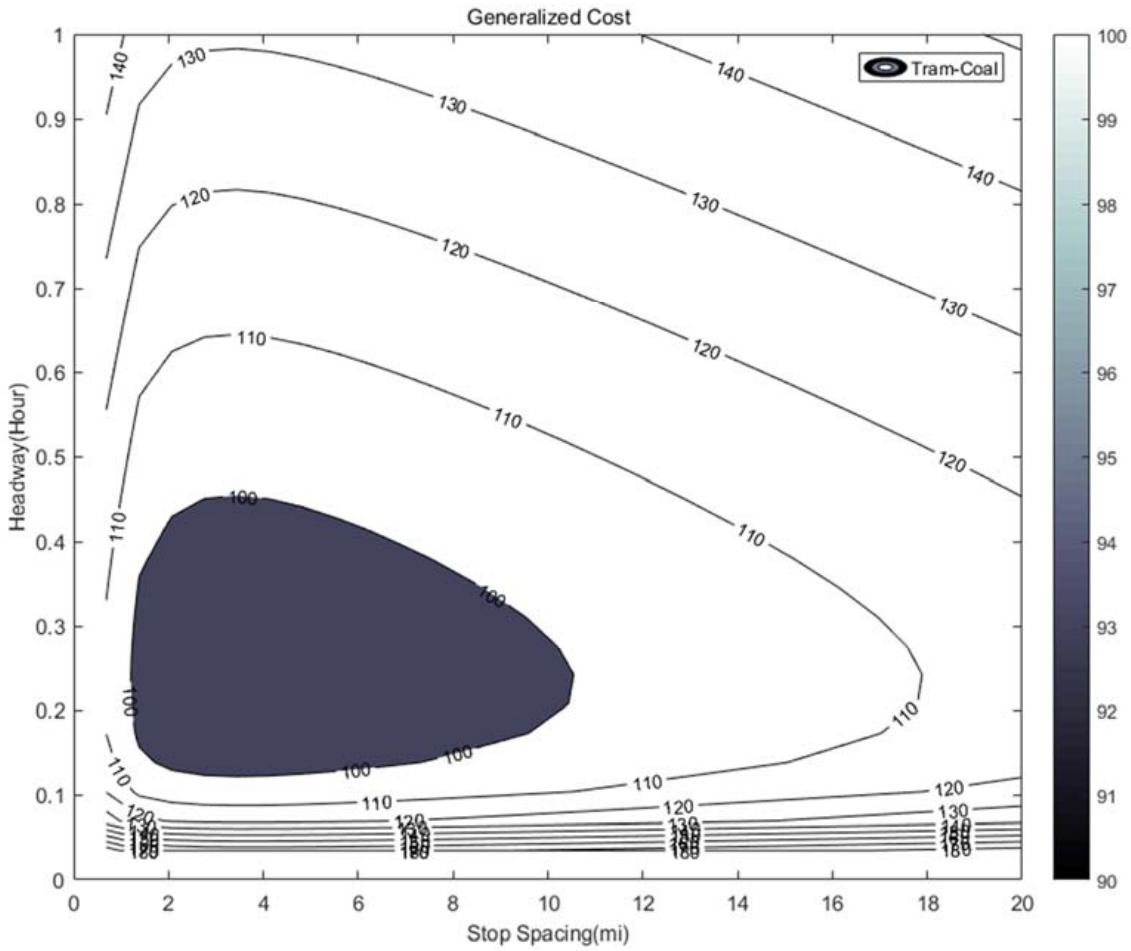


Figure 4.5. Effect of Tram's GC when Decision Variables (S, H) Change.

Again, using a lambda value of 20 trips per mile-hour and a value of time of $5 per hour, Figure 4.4 shows the effects of the generalized cost for LRT when operating with coal. Figure 4.4 shows a comparison of the generalized cost effects when the headway and stop spacing increase or decrease, assuming tram energy sources comes from different sources.

The contour graphs for LRT and tram shown in Figures 4.4 and 4.5 do not show any difference, as both optimal points are within the same contour line. However, the fact that the figures are similar does not mean the optimum points for both rails

are the same when the value of time is \$20 per hour with a variable demand rate of 5 trips per mile-hour and GHG emissions market price of \$20 per metric ton. A comparison of contour figures when tram and LRT gain their energy from different power plant sources shows that the optimum points are located in different spots.

4.4 Metro Heavy Rail Decision Variables on Generalized Cost

The literature review showed that when mega-wealthy cities faced an increase in traffic congestion, MHR was the most effective mode to remove some private vehicles off the road as well as improve air pollution. Despite the critics of emitting more GHG emissions when cleaner fuels are used, MHR might be the suitable mode to transport high volumes of passengers in wealthy cities. The evaluation of MHR to investigate how sustainable it can be was conducted, like all the other technologies that were studied in this research. Pareto frontier plots to show the trade-offs among the other technologies were created in Matlab to find the tipping points of demand rates trade-offs. Again, the inner circle of the contour graph contains the optimum point. When the metro receives its electricity from different power-plant sources, the optimum point is located in different inner circle.

4.5 Generalized Cost Optimization Problem

The following sensitivity analyses were performed using the main optimization function equation (4.1), which is listed below, to investigate the impacts of different variables in the proposed method on the GC and the GHG emissions. This optimization problem was used to perform the analyses in Sections 4.2 to 4.5.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & \text{Generalized Cost} = Z(S,H) \\ \text{subject to} \quad & S, H \geq 0 \end{aligned} \tag{4.1}$$

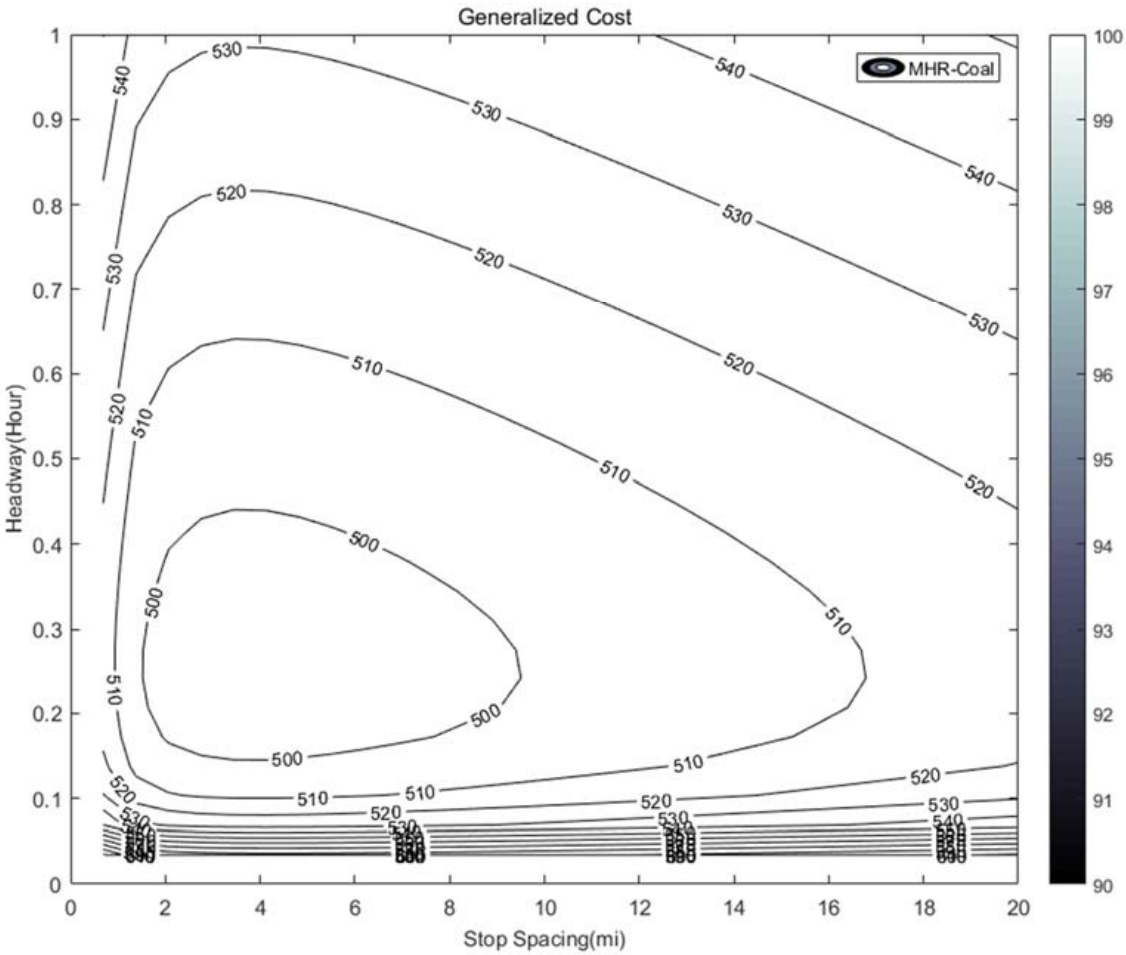


Figure 4.6. Effects of Decision Variables (S, H) on GC of MHR .

Solutions for a range of demand values (λ) are evaluated for a base case scenario: l= 8.1 miles, β = 15 \$/hr, γ = 20 \$/metric ton CO_2.

4.6 Level of Demands of Mixed Traffic and Dedicated Bus Lanes

One of the aims of this study was to investigate at what level of demand the trade-offs among public transit and private vehicles happen. As described in Section 3.3.3, the generalized cost of the private vehicles was calculating using equation (4.1). The variables used for the private vehicles calculations are listed in Table B.1 in Appendix B. Assumptions were that vehicle free-flow speed was 12.5 meters per second and traffic speed equaled 8.334 meters per second, with a traffic light cycle length of 60 seconds. Similarly to the trunk transit technologies, the emissions factors were calculated for all driving operation modes within a cycle. The calculated emissions factors can be found in Table B.4 in Appendix B. In regards to the generalized for the trunk, the characteristics of the base case scenario showing in equation (4.1).

Figure 4.7 shows where the trade-offs existed between operating a local or dedicated bus or a private vehicle, based on the three E's of the sustainability concept: environment, equity, and economy. These figures also show that as the value of users' time increased, the generalized cost of operating local and dedicated bus routes also increased. The figures also show that operating a the dedicated lane bus was more cost effective than that of a mixed traffic bus. Based on the range of the demand that was considered for the optimization, the level of demand rate significantly impacted the emissions cost of cars and local and dedicated bus routes. Figure 4.7 shows that as the demand increased, the cost of emissions per passenger decreased.

Table 4.1 identifies the exact tipping points for the trade-offs between operating a mixed traffic or dedicated bus route or a private automobile when β=\$15/hr. The findings show that sometimes the agency will need to decide whether to operate

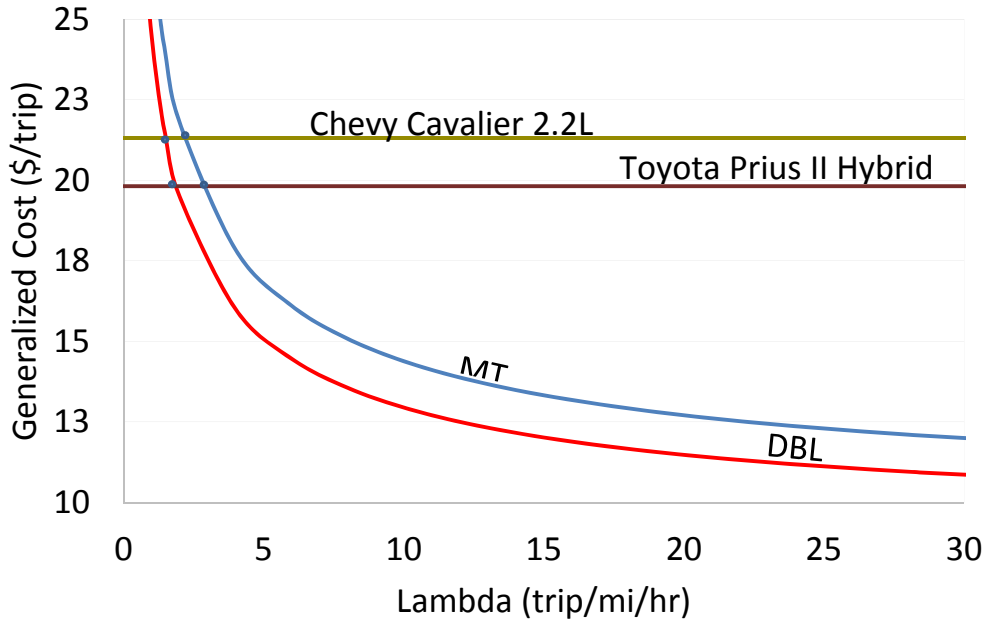


FIGURE a General Cost Tradeoffs between Buses and Private Vehicles ($\boldsymbol{\beta} = \mathbf{15\$/hr}$ & $\gamma = \mathbf{\$20/metric\ ton\ CO2 - eq}$)

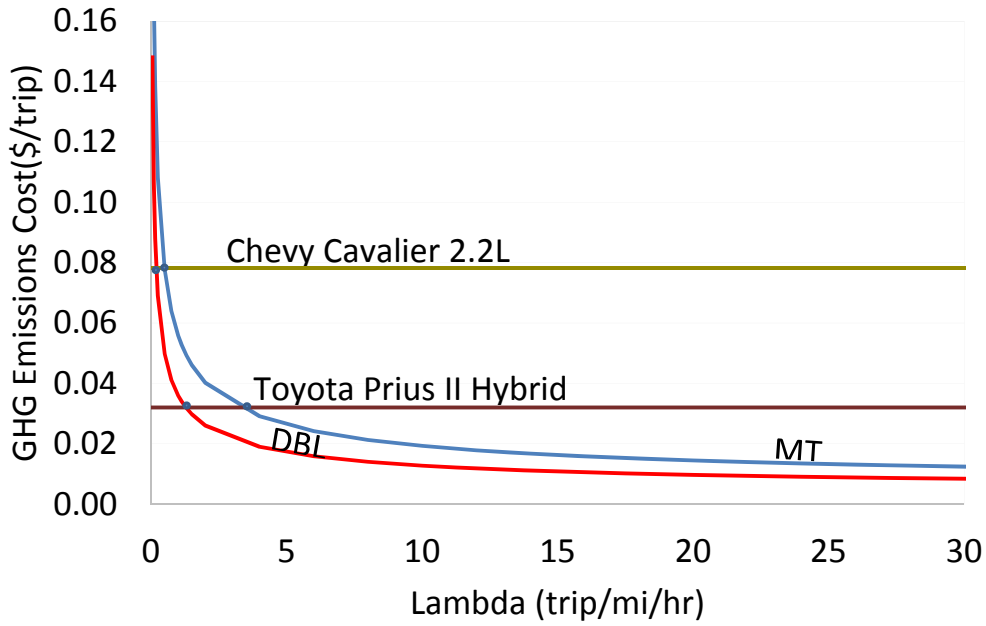


FIGURE b Emissions Cost Tradeoffs between Buses and Private Vehicles ($\boldsymbol{\beta} = \mathbf{15\$/hr}$ & $\gamma = \mathbf{\$20/metric\ ton\ CO2 - eq}$)

Figure 4.7. Generalized Cost and GHG Emissions Trade-offs between Buses and Private Vehicles.

smaller buses or provide an incentive to encourage users to drive low-emission cars. It was also noted that hybrid vehicles are more expensive, but they are capable of carrying more passengers with a lower emission cost per passenger.

Table 4.1. Tipping Point Demands (trip/mi/hr) that Justify Transit over Private Cars for β =\$15/hr.

Automobile Type	Mixed Traffic Bus		Dedicated Bus Lane	
	GC Basis	GHG Basis	GC Basis	GHG Basis
Toyota Prius II (Hybrid)	3.370	4.180	4.880	2.174
Chevrolet Cavalier 2.2L	2.730	0.591	4.220	0.295

Diminishing the GHG pollutants in an area sometimes might cost transportation policy makers and transportation practitioners. Some studies compared the costs of lessening GHG emissions with the individual medical costs that are affected by GHG pollutants emitted from non-environmentally friendly modes of transportation or other benefits of having clean air that is free of GHG pollutants. In this study, an evaluation was performed to examine how much it would cost transportation policy makers to encourage travelers to adopt a more environmentally friendly mode of transportation.

The difference among the trade-off points between transit modes and private vehicles was determined. Figure 4.8 shows the results of optimization the generalized cost with the lambda values where the trade-offs happen among public transit and private cars minus the generalized cost value of private vehicles divided by the GHG emissions optimization with lambda where the GHG emissions trade-offs happen minus the GHG emission of private vehicles using the base case scenario as described above. Figures 4.9 and 4.8 show the comparisons of emissions to switch travelers to the most sustainable modes when rails receive its electricity from burning coal or nuclear offshore, respectively. Figures 4.8 and 4.9 were plotted with the difference of costs between public transportation and private vehicles divided by their difference

in GHG emissions costs. In some cases, the generalized cost is already lower than that of private vehicles so the curve is switched to the opposite way. Overall, it was found that the cost of moving travelers to the most cost effective mode(s)was higher compared to the modes that were found to have the highest generalized costs.

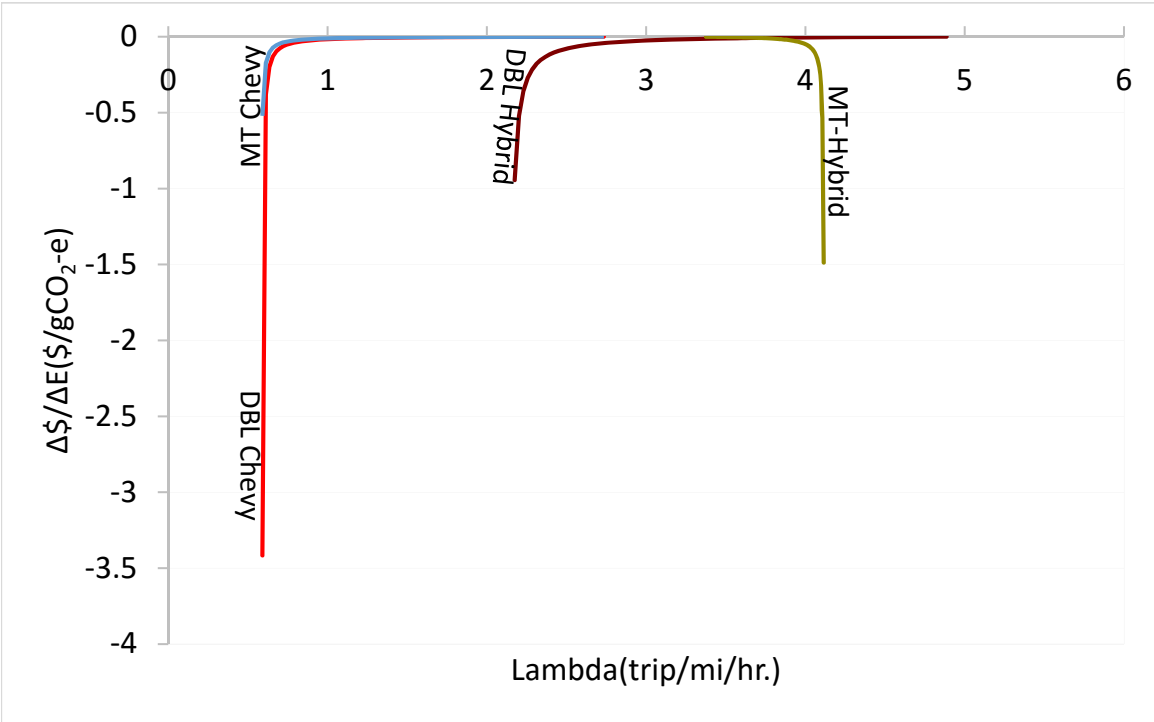


Figure 4.8. Cost of Moving Travelers to Sustainable Modes to Reducing Emissions

4.7 Sensitivity Analysis

This study focuses on a multimodal analysis where several modes of public transportation were evaluated. This chapter explains the sensitivity analyses that were performed for each mode using the results of the Matlab optimization of the general cost function considering a static traffic network case study. Section 4.3 focuses on the generalized cost effects when the variables are changed to a 20 percent lower and higher value of the base case value. Section 4.4 focuses on investigating the effects of

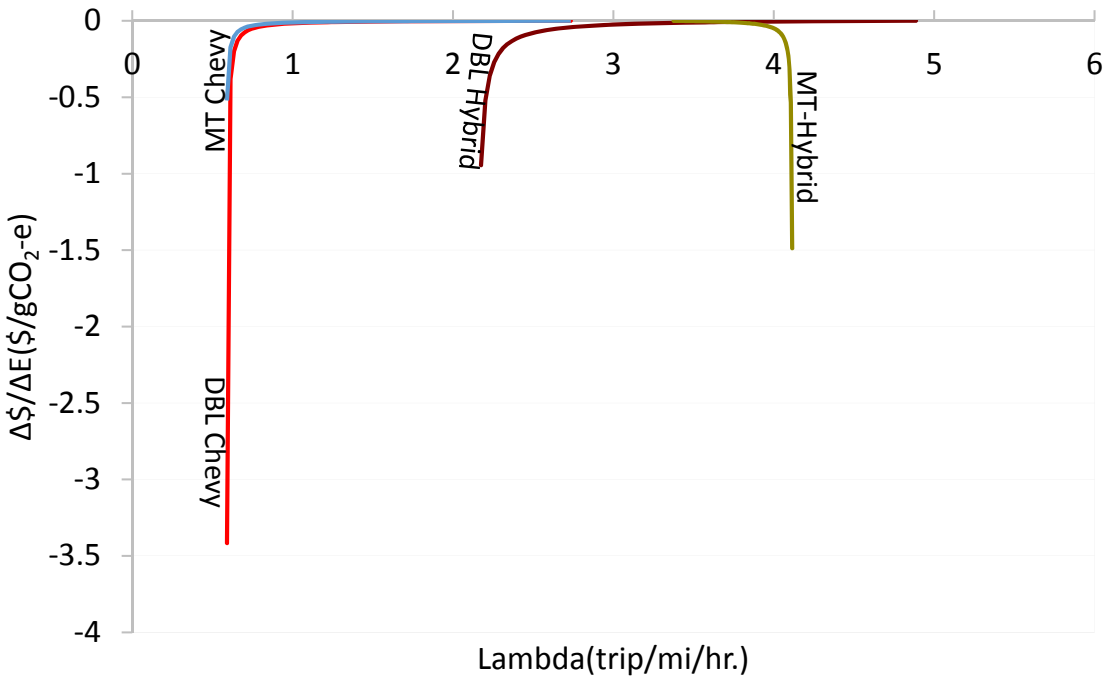


Figure 4.9. Cost of Moving Travelers to the Mode to Reducing Emissions.

generalized cost when the emissions factors of all modes were changed to 20 percent lower and higher than the base case value.

4.7.1 Generalized Cost of Mixed-Traffic and Dedicated Lane Buses

The first part of the analysis consists of comparing two diesel buses, where one is operating in mixed traffic while the dedicated bus has its own ROW. However, this study assumed that both buses have the same characteristics, with one operating in mixed traffic and the other using a dedicated lane. In this network, the author assumed a multi-modal network corridor with private vehicles and other transportation modes.

To evaluate the impacts of the demand variables on the costs, a sensitivity analysis was conducted using case scenarios. In addition to the fixed model parameters listed above, three variables were considered that characterize the demand and societal value of GHG emissions with sets: beta (β) using a lower value of 10 and a higher

value of 150 \$/hr; lambda (λ) with a lower value of 0.001 to 1000 in trip/mile/hour; and gamma (γ) of 2 to 200 in \$/metric ton CO2e.

One of the sensitivity case scenarios was conducted by using a 20% sensitivity analysis case scenario with lambda (λ), beta (β), and gamma (γ) equal to 10, 15, and 2×10 respectively as the base values. The percentage low, base, and high values that were calculated are listed in Table A.8 in Appendix A for both local and dedicated buses. The findings show that the percentage change of the emission value did not have a big impact on the general cost of operating local and dedicated lane buses, whereas the value of time and the arrival rate had a greater impact on the general cost of operating both types of buses.

Another case scenario of this sensitivity also investigated the effects of acceleration and deceleration on the general cost. The following figures were obtained by using a base acceleration and deceleration value of ± 0.89 miles per second squared with the same 20% change for lambda (λ), beta (β) , and gamma (γ). Using a 20% change of ± 0.89 mile per second squared, the EF_s of 190.31, 174.88, 167.18 gCO_2 per stop were calculated using the VSP emission rates for low, base, and high values respectively.

Comparing the findings from Table A.8 and those from ± 0.89 miles per second squared acceleration and deceleration base case scenario above for the mixed and dedicated bus lanes, it was found that the general costs of both buses increased when accelerating and decelerating at a slow rate. The length or the size of the bus that is stopping and then accelerating at every stop along the route was not considered in this study. Indeed, the flow of traffic can affect the timing of acceleration and deceleration when leaving and approaching a stop, respectively, but the study focused on a static traffic network with the assumption that the route was not congested. To evaluate the concrete situation, a case scenario was used that assumed an acceleration and deceleration for the buses that were within the real-world range. Hence, a sensitivity

case of ±1 meter per squared second of acceleration and deceleration was conducted. Figure 4.10 and Table A.9 show the findings of the latter scenarios.

Figure 4.10 shows the tornado graphs that display the effects of the variables on the general cost for both mixed and dedicated bus lane. In Figure 4.10, the two graphs show the tornado graph using 20 percent of 2 meter per squared second of acceleration and deceleration of base case scenario of mixed and dedicated bus lane.

4.7.2 Generalized Cost of Full Bus Rapid Transit (BRT)

Considering BRT's characteristics, mixed traffic and dedicated bus appear to fit within the same category of buses, except, in some situations, a full bus rapid transit can have a higher potential due to its enhanced characteristics, namely, speed, station or shelter, and others. The full BRT mode GHG emissions model is similar to those of the mixed traffic and dedicated bus lanes, except the variable inputs were selected based on previous full BRT findings. Hence, the VSP method was initially used to model the emission factors needed to plug into the analytical model of the full bus rapid transit mode. To estimate the emission factors for the full BRT, this study used deceleration and acceleration rates of ±1 (m/sec^2). Similarly, several input variables were randomly selected to run some sensitivity case scenarios for the full BRT. The outputs of the sensitivity analyses are shown in Table A.10 and the tornado graph in Figure 4.11.

Interpreting the sensitivity results for the full BRT mode, the results show that the value of time (i.e., beta) has the most significant impact on the general cost. The demand rate appears as the second variable that has a higher impact on the generalized cost. All the other variables listed also have impacts on the generalized cost, but the impacts are very minimal as shown in Table A.10 in Appendix A. The results of the sensitivity analyses can also be explained in several other ways to facilitate the decision making of transit agencies. As previous studies have revealed,

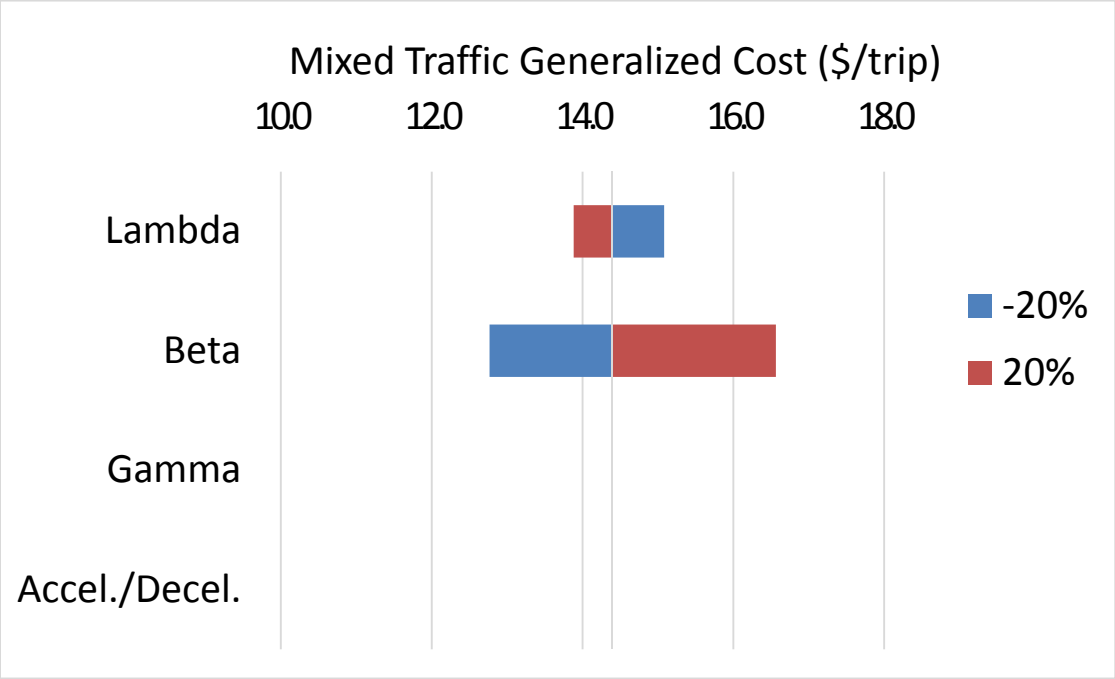


FIGURE a Mixed Traffic Bus 20% Accel. /Decel. Change

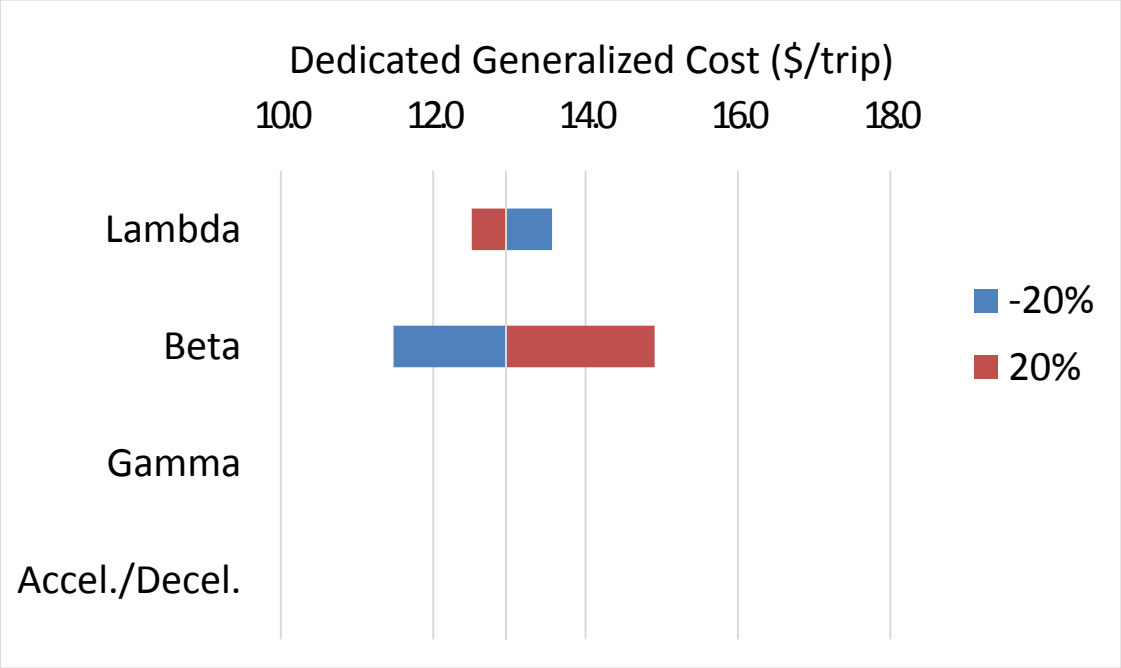


FIGURE b Dedicated Bus Lane 20% Accel. /Decel. Change

Figure 4.10. Cost of Moving Travelers to the Mode to Reducing Emissions.

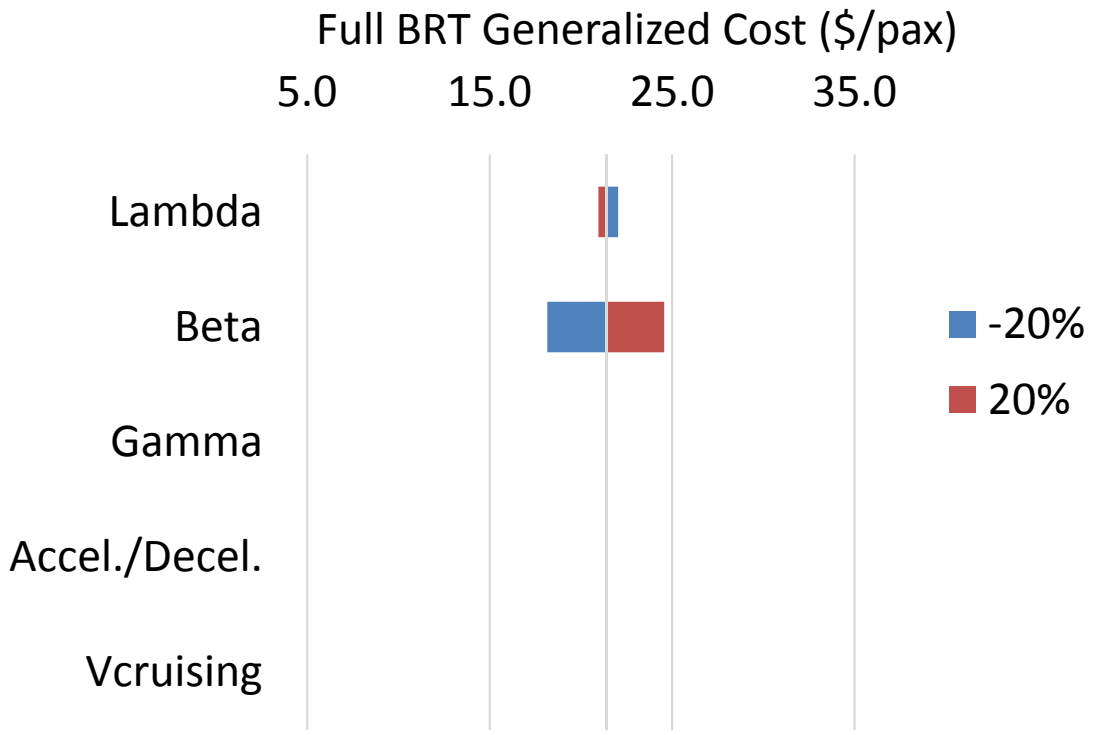


Figure 4.11. Full BRT 20% Change on Generalized Cost.

the demand rate is one of the important criteria that transit agencies can rely on when planning or designing a transit route in a corridor while accounting for all three E's of sustainability. The other variable that transit agencies can use to predict how potential travelers use the planning mode is the value of time. Clearly, in all case scenarios, the value of time of the passenger appeared as the second variable that had an impact on the generalized cost.

4.7.3 Generalized Cost of Rail Transit

In this study, it was assumed that the capital, operation, and maintenance cost of a tram and light rail transit route are the same. The study focused on investigating a 6-axle tram, light rail transit, and metro heavy rail transit. Furthermore, the emission factors were calculated using the methodology described above in Chapter 3, Section 3.3.4. However, the model to calculate the GHG emissions cost of both modes were differed because the light rail that was investigated in this study is operating in its own exclusive ROW, while the tram mode at some point is assumed to operate with mixed traffic. To investigate the effect of emissions on the general cost, several electricity sources, such as coal, natural gas, nuclear and wind offshore, and solar photovoltaic (PV)-utility were considered. The gCO_2-equivalent emission conversion factors found in (Schlömer et al., 2014) were used to convert the emission rates in gCO_2e for the tram, light rail, and metro heavy rail modes. Unexpectedly, nuclear and wind offshore energy sources had the same gCO_2e. Figures 4.12 and 4.14. Additionally, a comparison of the sensitivity results of coal and nuclear/wind offshore energy sources are shown in Appendix A.

Four different types of energy sources were also investigated to compare the effects of using different energy sources to operate rail transit technologies. The figures in this section compare the sensitivity results of metro heavy rail, tram, and light rail. In all cases, the demand rate and the value of time were found to have the same

significant on the general cost when electricity came from different sources. However, the cruising speeds for each case were found to be different. The other variables appeared to have little impact, no matter where the energy to operate the train came from. Figure 4.13 shows a case scenario where the rail is electrically powered from a natural gas energy source. The cruising speed for light rail has a greater aspect in Figure 4.13. The latter can be explained due to the fact the light rail uses an ROW category A.

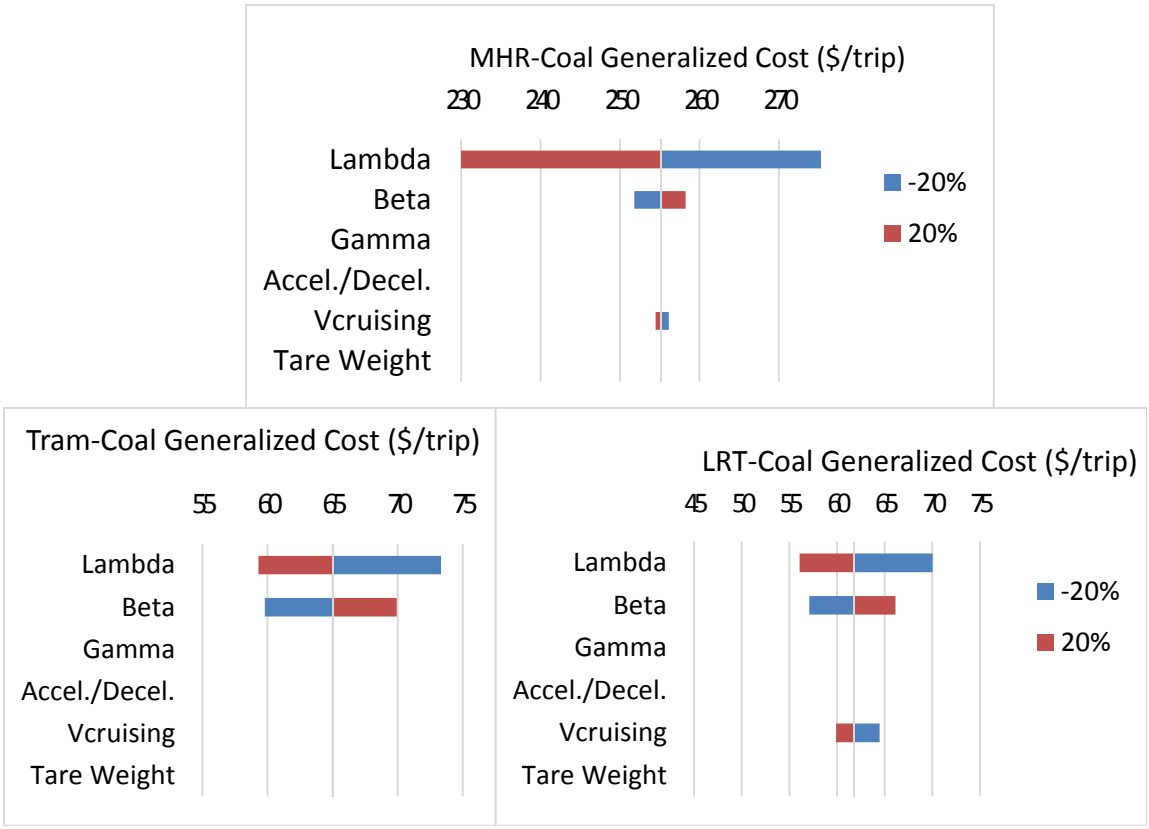


Figure 4.12. Rails 20% Accel./Decel. Change- Energy Source: Coal.

In addition to investigating the effects of the different input variables on the generalized values of all trunk technologies, the author also explored the effects of the generalized cost when constraints were set on the headway, the capacity of the vehicles, and the distance between the stop spacing along the route. In all cases, the

generalized cost of metro heavy rail was found to be the highest among the rest of the technologies. However, with the increase of value of time of the passengers, an MHR route can serve to meet the requirements of transportation users to reach their destinations more quickly. Having the potential to transport passengers faster makes metro heavy rail a competitor a full BRT. However, the literature review suggests that metro heavy rail is more sophisticated and therefore more appropriate for big cities in the United States and Europeans.

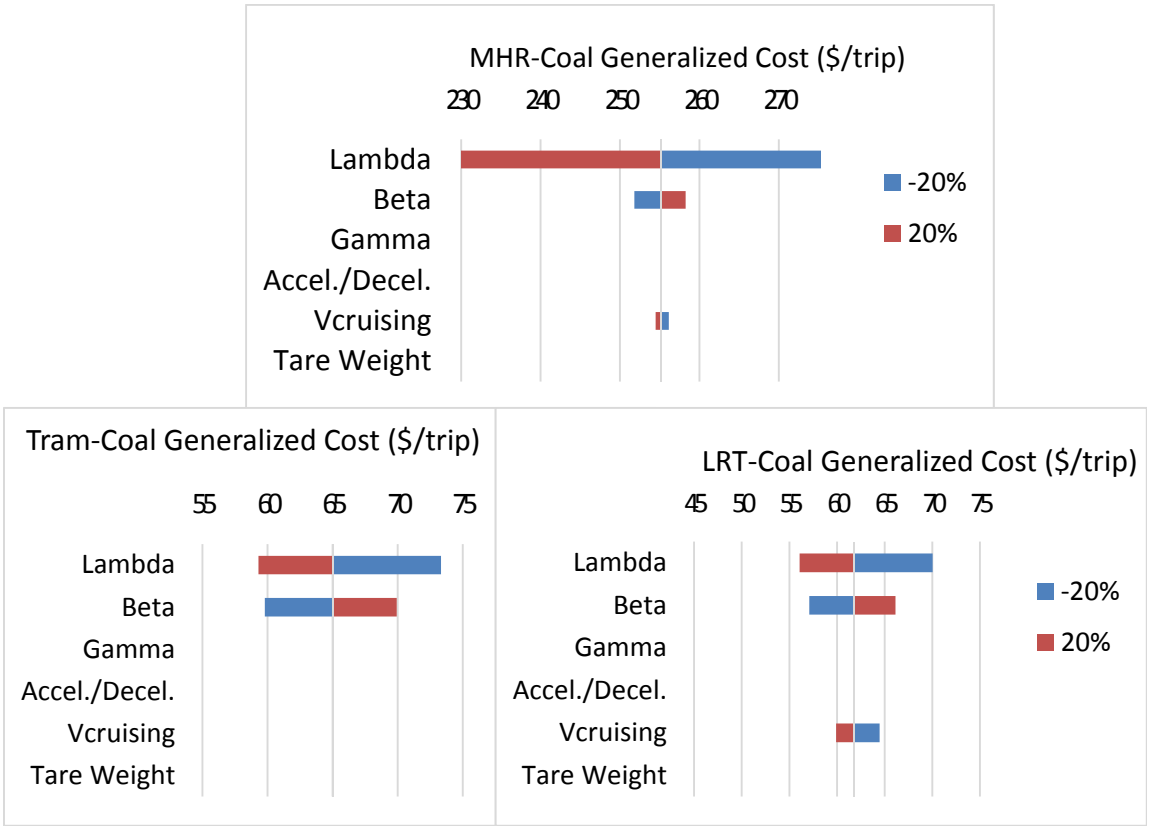


Figure 4.13. Rails 20% Accel./Decel. Change- Energy Source: Nuclear/Offshore Wind.

The decision making based on the generalized cost has been evaluated by comparing the findings when rails gains its fuels from burning coal and nuclear offshore power sources. Figure 4.14 shows the comparison.

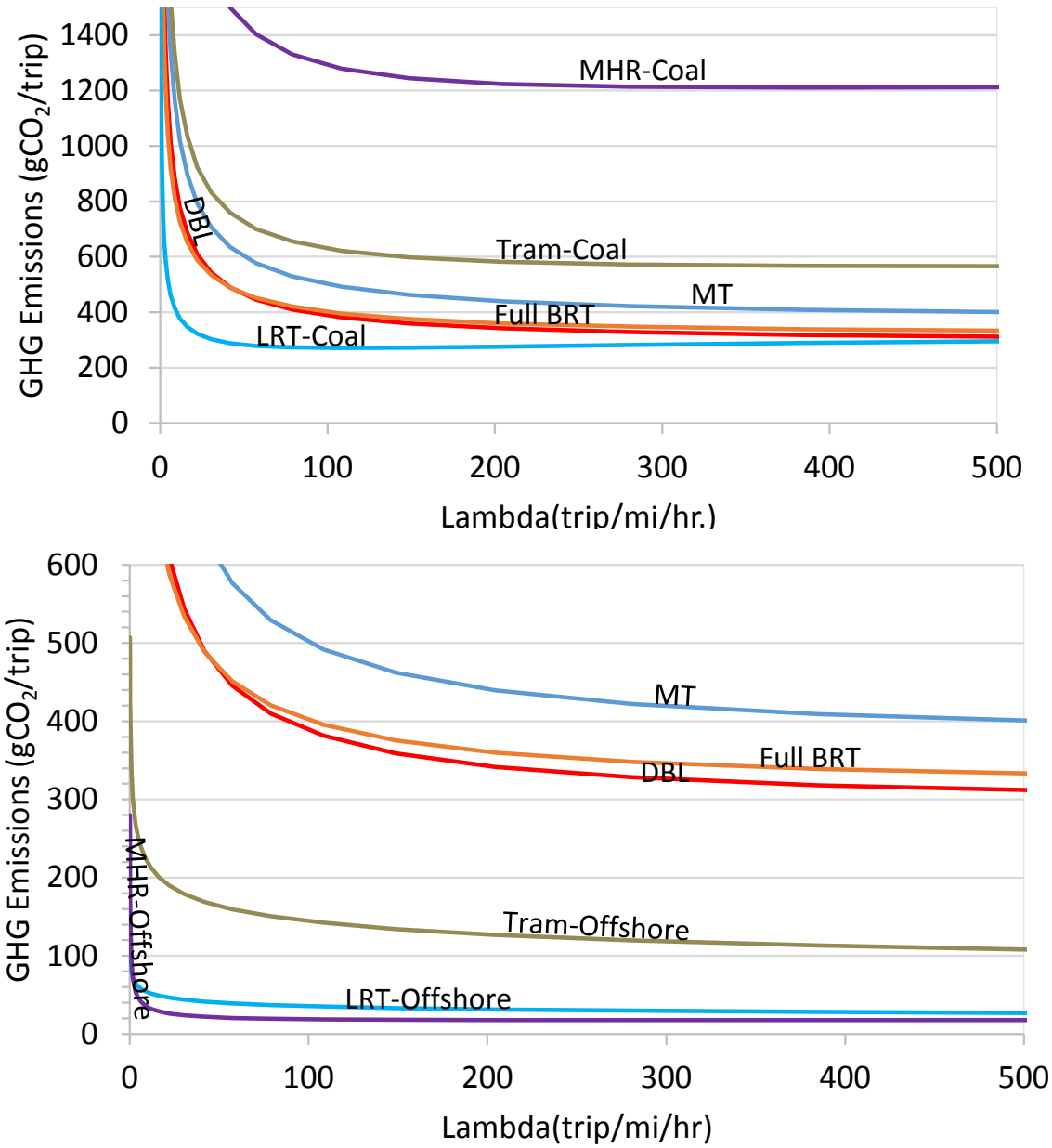


Figure 4.14. GHG Emissions when Rails Powered with Coal and Nuclear Offshore.

4.7.4 Greenhouse Gas Emissions Effects Public Transportation Modes

One of the major contributions of this study is the investigation of the environmental impact trade-offs among the other aspects of the sustainability concept. GHG emissions had to be converted into dollars to enable the simultaneous analysis of all three E's of sustainability in this study: environment, equity, and economy. Using the VSP emission factors provided the option to separately evaluate the emissions during different modes operating in the driving cycle. The following findings show the sensitivity scenarios of the emission that have been created as when the vehicle are in the acceleration and deceleration, idling, and cruising modes.

The findings of the sensitivity analyses that explored the effects of different input variables and the emissions rates during the different operation modes, namely, idling, cruising, and stopping on the generalized cost of emissions reveal that demand rate, value of time, and cruising speed have significant impacts on the generalized cost. In terms of emission factors for the different operation modes, the cruising mode emission has a higher impact on the generalized cost. The latter can be interpreted as the technologies are most likely spending the majority of the length of the route within the cruising mode along the corridor, and sometimes interruptions by traffic delays or other inconveniences during different times of the day might have negative impacts on the amount of emissions that are produced during that phase. Although, the idling emissions seem to be the lowest, which again agrees with the real-world scenario, as the technologies are simply using the electricity for heating or cooling during the idling phase.

A sensitivity analysis of emission factors was conducted to quantify the effect of increasing and decreasing the emission factors for all driving modes and transit vehicle modes by 20% on the optimized generalized cost. Tables A.11 and A.12 in the appendix show the results of the 20 percent sensitivity analysis for MT and DBL.

Full bus rapid was also evaluated using similar percent on the GHG emissions for all three operation modes. The results are shown in Table A.13 in Appendix A.

Indeed, the cost of GHG emissions per trip was found to be very small when concurrently quantifying all aspects of sustainability according to one of the findings of this study. Nevertheless, the emissions of gram of CO_2e per trip were found to be much higher and also were within the same range that previous studies have found. According to the findings of this study, the GHG emissions in gCO_2e per trip can be ranked for the base case lambda, beta, and gamma values from metro rail, mixed, DBL, full bus rapid transit, tram, and light rail transit, from higher values to lower values, respectively using the base case scenario mentioned above in Section 4.2. However, when the length of passenger trip changes, the GHG emissions rank varies among the modes.

Other evaluations were performed to scrupulously investigate the environmental impacts. Using the base case scenario variables, all modes were plotted. When the emissions cost reached $150 per metric ton, the number of vehicles per hour when planning or operating sustainable multimodal transportation routes was found to be the same compared to $20 per metric ton GHG emissions cost for some modes.

An example of the latter scenario can also be a metro rail transit that has gained electricity from a coal source and a DBL as shown in Figure 4.18. Furthermore, when operating light rail transit, metro rail transit, mixed, and DBLs, and the cost of emissions reaches $150 per metric ton, transit agencies and planners again face a face a trade-off between operating more vehicles in order to provide fast travel times for users or operating fewer vehicles to save operating expense and reduce emissions. At this point, the transportation operations research expertise will come in handy to apply the Pareto optimal concept to assist in facilitating the decision making of the latter scenario. On the other hand, when operating a tram, the opposite happens, where when the cost of GHG emissions is higher, more buses are running compared

to the lower cost of emissions for the same demand rate. One scenario that can explain the reason for operating more buses when the GHG emissions cost reaches $150 per metric ton is the fact that in this research, the author assumes that the only criteria that distinguishes a tram from an LRT is the traffic conditions, because light rail transit is studied as an exclusive ROW, while the tram is operating within traffic in addition to stopping for traffic signals. Focusing on the number of riders per hour of a tram, one can assume that the stopping time might affect the scheduling of the vehicles and therefore, transit agencies might sometimes have to operate more vehicles, even though the cost of GHG emissions is high, to maintain an efficient schedule for the tram.

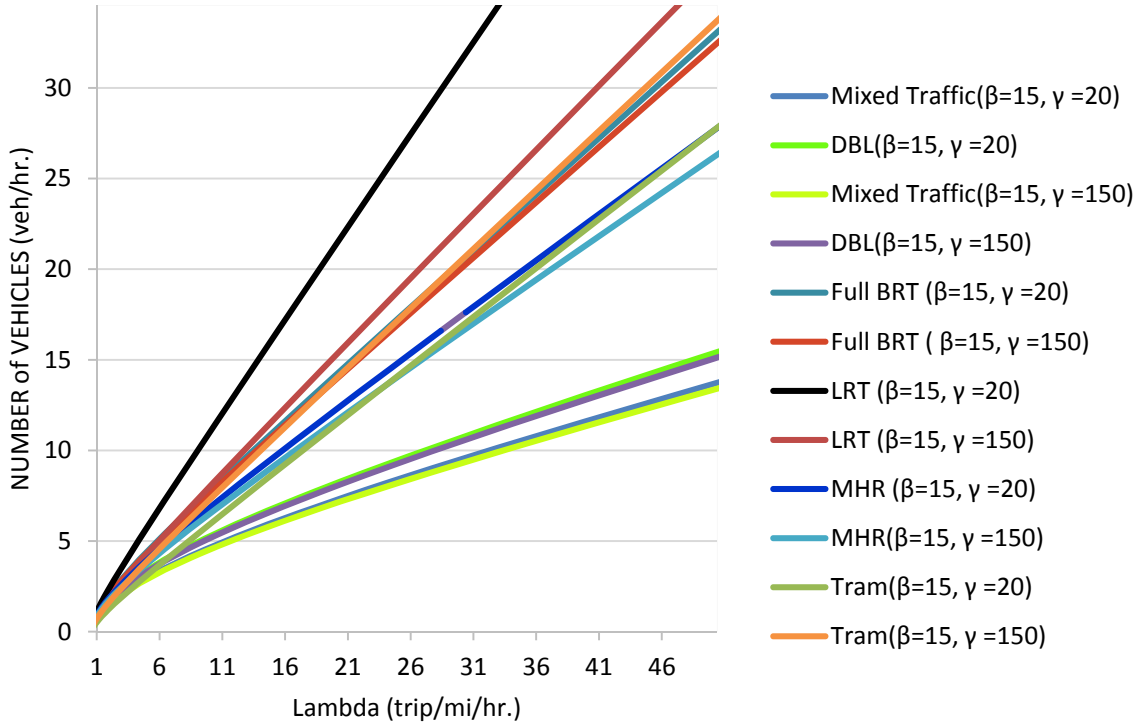


Figure 4.15. Level of Demands Effect on Vehicle Frequency.

Taking into account the environmental impacts of all trunk technologies in this study, the monetized travel time vis-*à*-vis the emissions cost per passenger was plotted. Figure 4.15 shows the trade-offs between the MT and the DBL, for example,

when the monetized travel time of the traveler is approximately $15.95 per hour and the emissions cost per user is within $0.054 per passenger. Figure 4.15 also shows that the monetized cost increases with the increase in emissions cost per passenger.

4.8 Comparisons of Generalized Costs for Optimized Transportation Routes in a Corridor

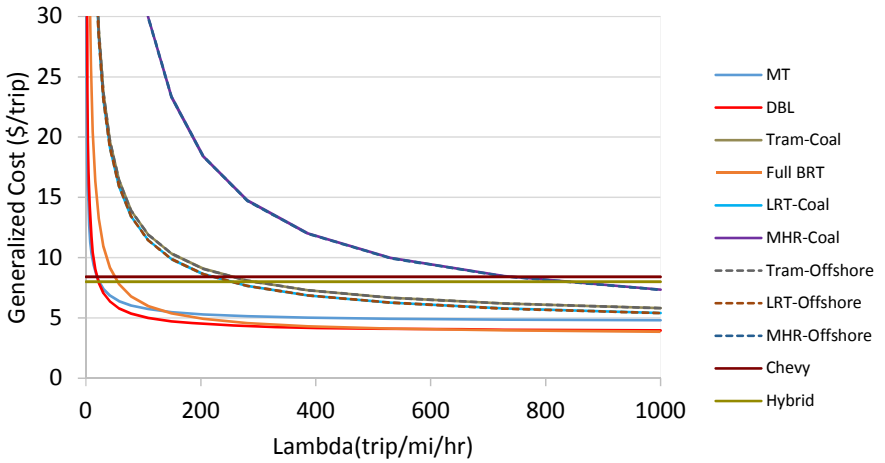
The following figures show a comparison of different modes that were investigated in the linear corridor using the base case scenario. Figure 4.16 shows the trade-offs among all modes in the corridor, breaking down each aspect of the sustainability cost.

Figure 4.17 breaks down the effects of all three aspects of sustainability on the travel demand, the value of time, and the market price of GHG emissions. In Figure 4.17, a comparison of different case scenarios using different passenger average trip is shown to investigate the impact of length of travelers' trip on the general cost. Different types of fuel were used for the trunk transit technologies to compare the generalized cost values.

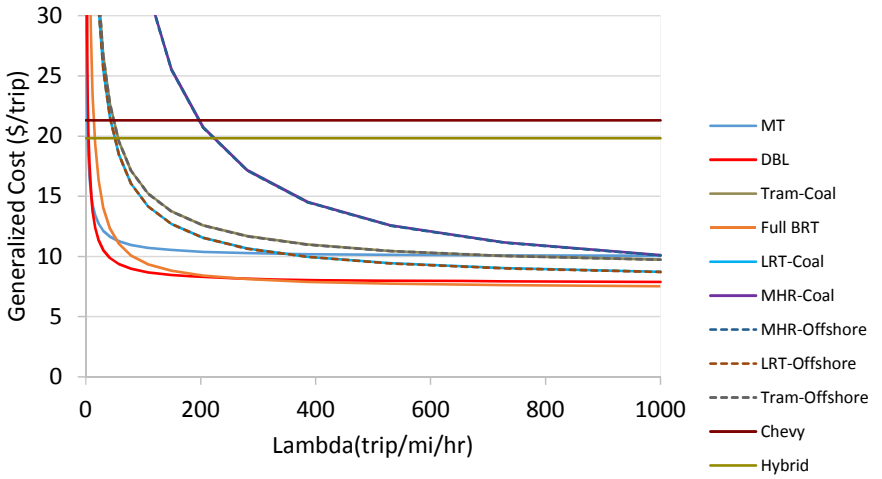
The effects of the emissions market value were explored to synchronize the impacts of GHG emissions cost on the decision making of choosing a transportation mode for a city. Figure 4.18 shows that show the findings.

4.9 Phase Diagram Evaluating All Studied Trunk Technologies

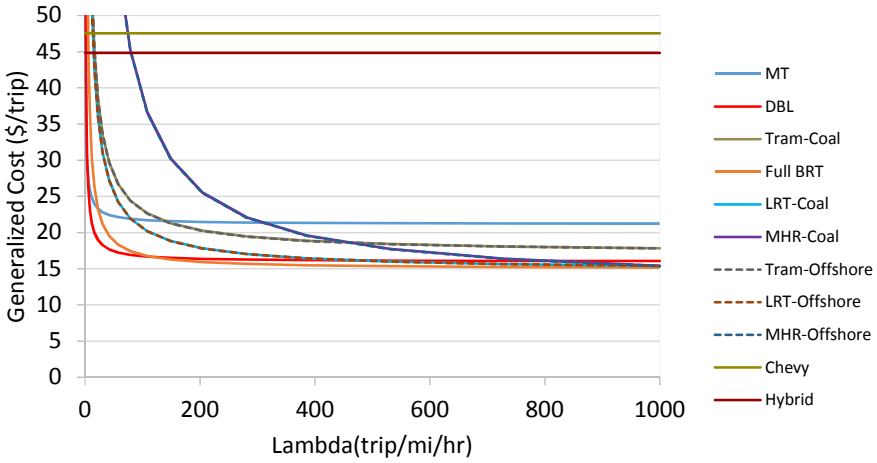
In addition to exploring the effects of emissions on the generalized cost, this study investigated sustainable multi-criteria decision making to assist transit agencies or stakeholders in choosing a mode that is suitable for any city, assuming the traffic state is static and the demand rate is constant. The investigation of this part of the decision-making analysis used a specific headway, stop spacing, lambda, beta, and gamma when optimizing the general cost subject to the capacity constraint. The



(a) Average Passenger Trip Length=3 mi



(b) Average Passenger Trip Length=8 mi



(c) Average Passenger Trip Length=20 mi

Figure 4.16. Generalized Cost Trade-offs Among all Modes with Different Avg. Trip Length.

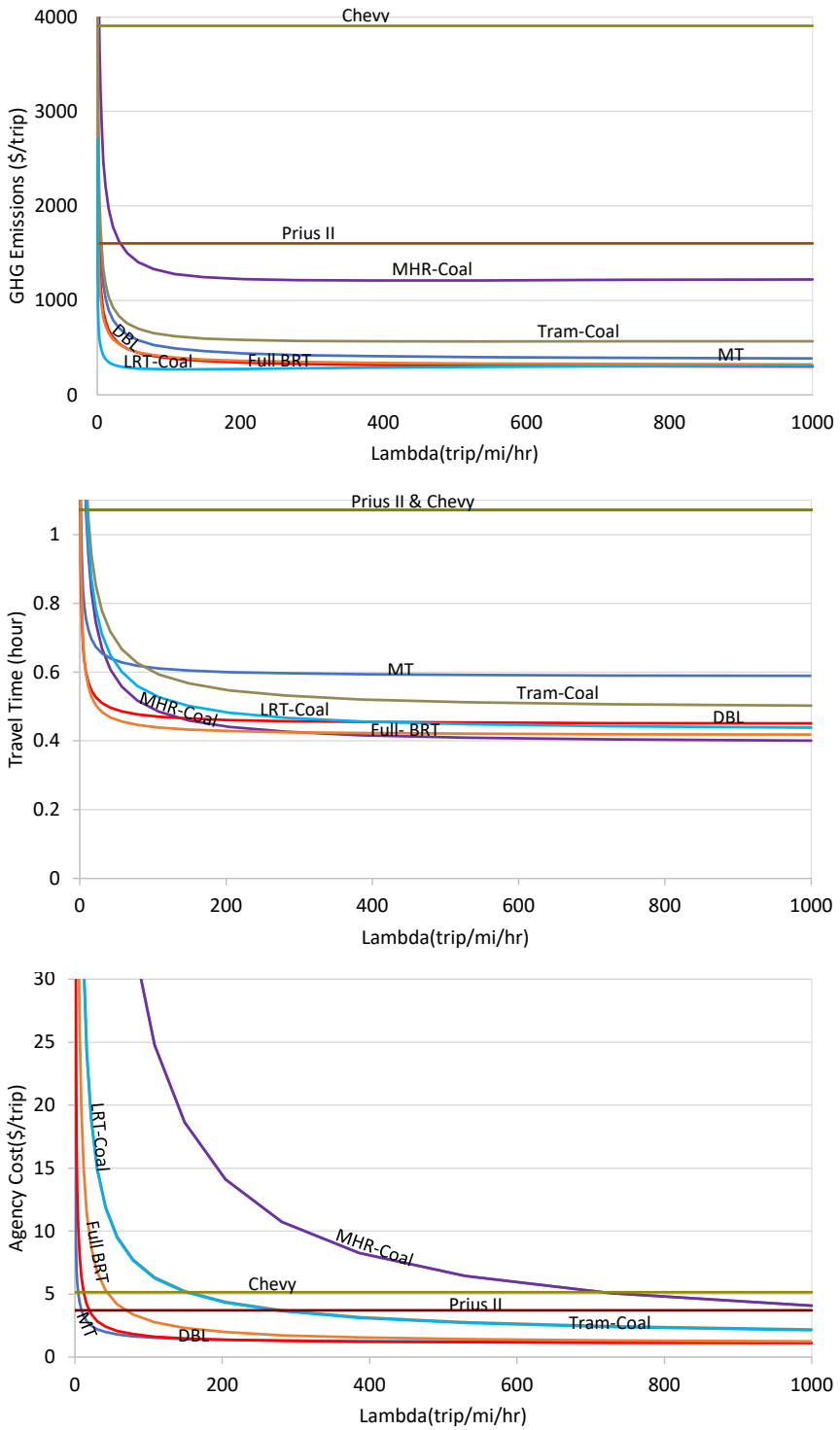


Figure 4.17. Components of Generalized Cost: GHG Emissions, Travel Time, and Agency Cost

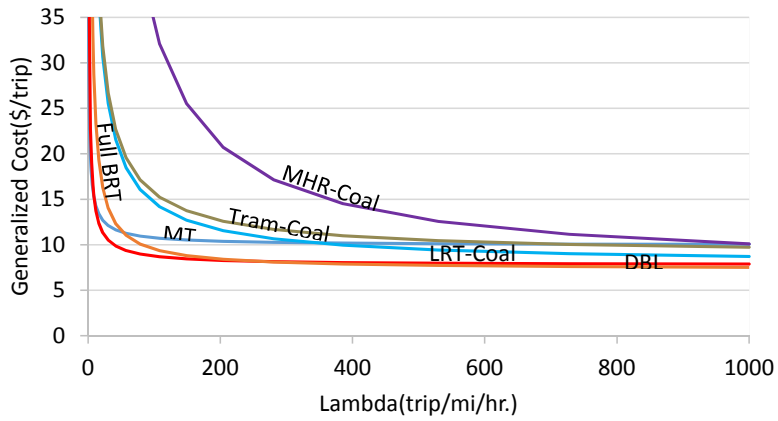


Figure a: Effect of GHG Emissions Market Price on GC (Rails use Coal, β=$20/hr & ɣ =$0/metric ton)

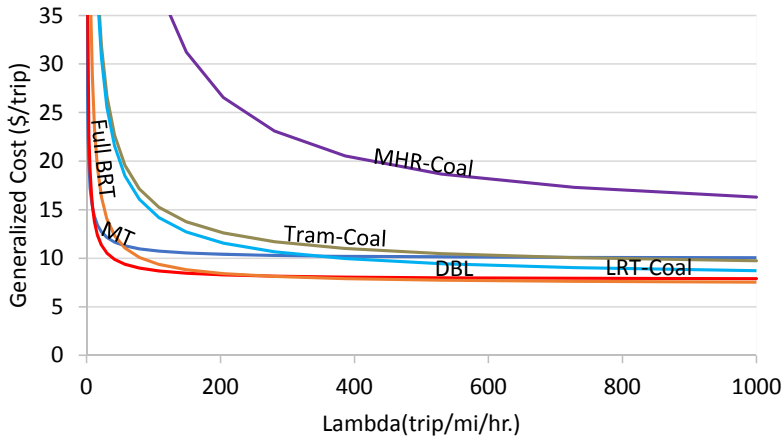


Figure b: Effect of GHG Emissions Market Price on GC (Rails use Coal,β=$20/hr. & ɣ =$20/metric ton)

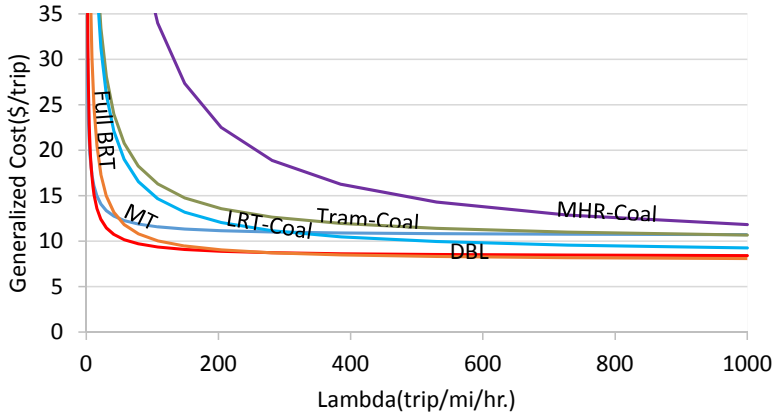


Figure c: Effect of GHG Emissions Market Price on GC (Rails use Coal,β=$20/hr & ɣ =$2000/metric ton)

Figure 4.18. GHG Emissions Market Value Effects on Sustainable Public Transit Mode Decision-Making.

following case scenarios were selected to compare the cheapest mode for a city that had the following constraints: beta= \$20/hr., lambda=5 trip/mi/hr., gamma=\$20 per ton CO_2, and a range of headway and stop spacing. In this case scenario, the full bus rapid transit mode was found the most effective mode, but at some specific demand rates, the DBL was also the most effective mode.

It is common in any country to conduct monthly or yearly customer service ridership surveys to improve continuously operating efficient transportation to the populace. To gather that information, all types of methodologies have been used by transit agencies. Based on the outcome of the latter data, transit agencies might plan on introducing new technology or strategies, or redesign some routes by setting up limitations on the stop spacing along the route as well headway of the vehicles. The framework of this study can be used pragmatically to handle similar scenarios. Therefore, the second optimization function explored the scenario where travelers might at certain times switch to a transportation mode that better meets their criteria if they are either dissatisfied with the current service or have an income increase that allows them to purchase private vehicles. To model such scenarios, the agency plus the user costs (AC + UC) were combined as one single generalized cost function that the author refers to as social cost, and was minimized subject to the vehicle capacity, GHG emissions cost, and GHG emissions in grams per CO_2e, with specific constraints on both the GHG emissions cost and gram CO_2e. The following figures show the comparison of GHG emissions cost and gCO_2e of one case scenario. Furthermore, all trunk technologies that were studied in this research were also evaluated in this part of the analysis. In some cases, the capital costs of mixed traffic and DBL were assumed to be zero. But the figures show in this dissertation take into account the capital cost of all studied transportation modes.

Figures 4.19, 4.20, 4.21, 4.22 , and 4.23 show mesh graphs to identify the technology that is the most dominant when assuming a value of time for gamma is $20 per metric ton.

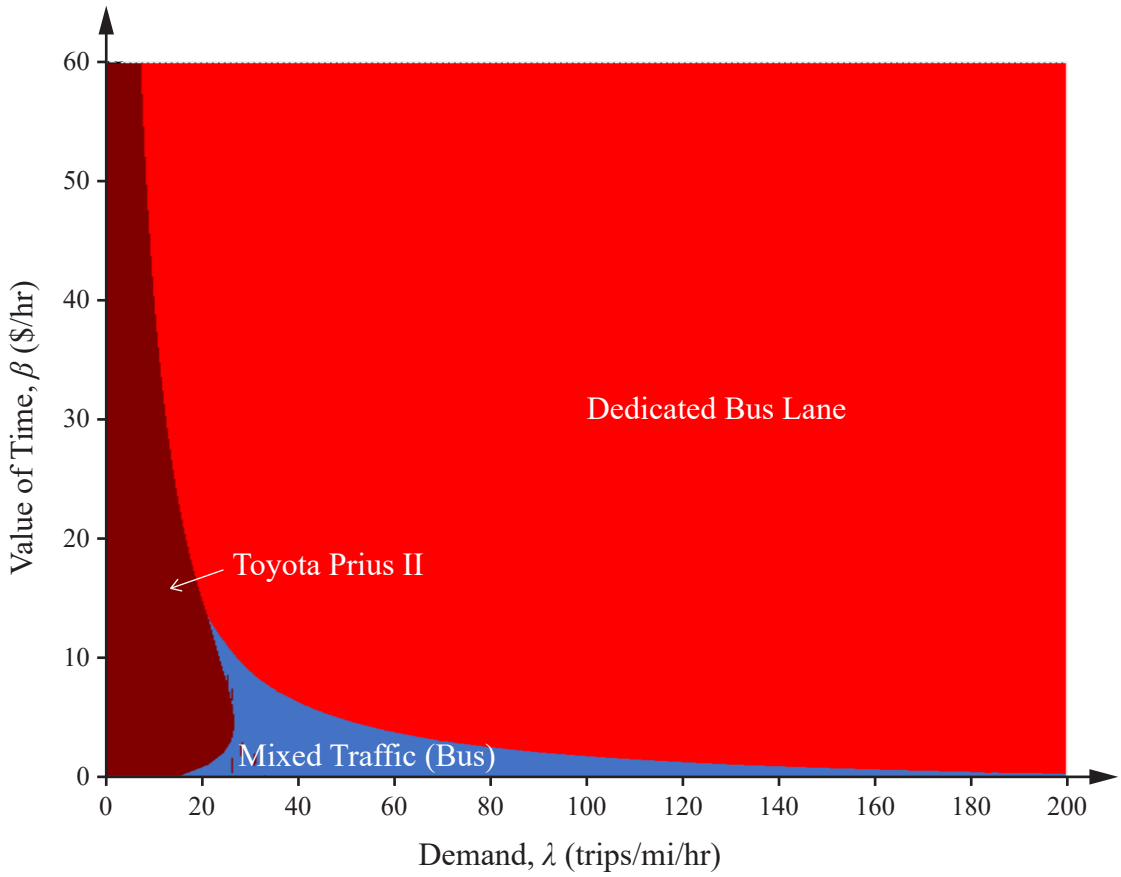


Figure 4.19. Decision-Making Support Tool with Multiple Objectives and Constraints with Avg. Trip Length=3 mi

Figure 4.20 shows the most cost effective modes when the generalized cost is 0-0.5 x 104 dollars per trip and an average trip length of 20 miles. However, when the demand is 400-1000 trips per mile per hour, trade-offs occurred among metro heavy rail, tram, and the Chevy. With the assumption of using existing infrastructure for MT and DBL, a DBL is the most cost-effective mode. Adding the cost of infrastructure, MT is more cost-effective than a DBL and the Full BRT when the level of demands has increased.

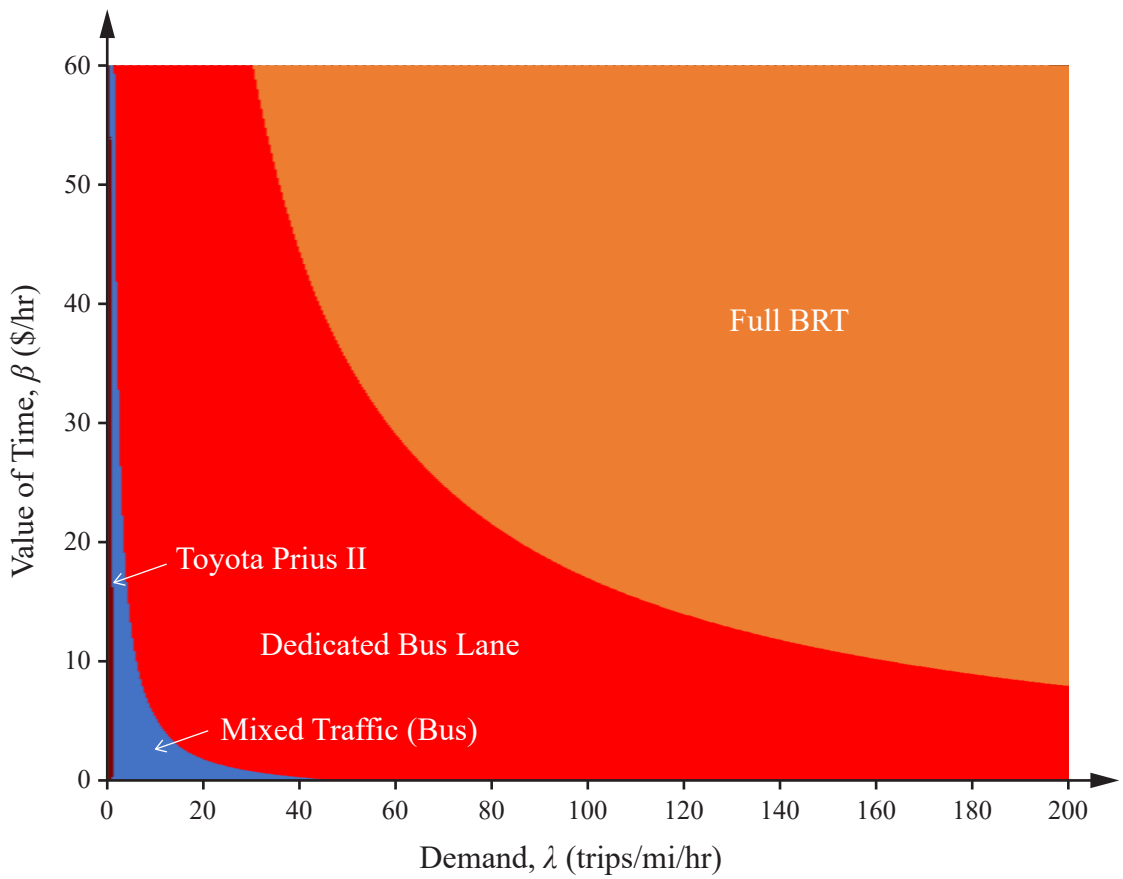


Figure 4.20. Decision-Making Support Tool with Multiple Objectives and Constraints.

However, evaluating all modes in terms of users' value of time and lambda with the capital cost for all modes including, Figure 4.21 shows that a DBL is the most cost-effective. But when the demand is very low, a trade-off among the hybrid vehicle and the DBL happens. The latter brings up a policy question to investigate: whether to provide a smaller bus or to offer equitable incentives to encourage travelers to purchase low-emissions vehicles.

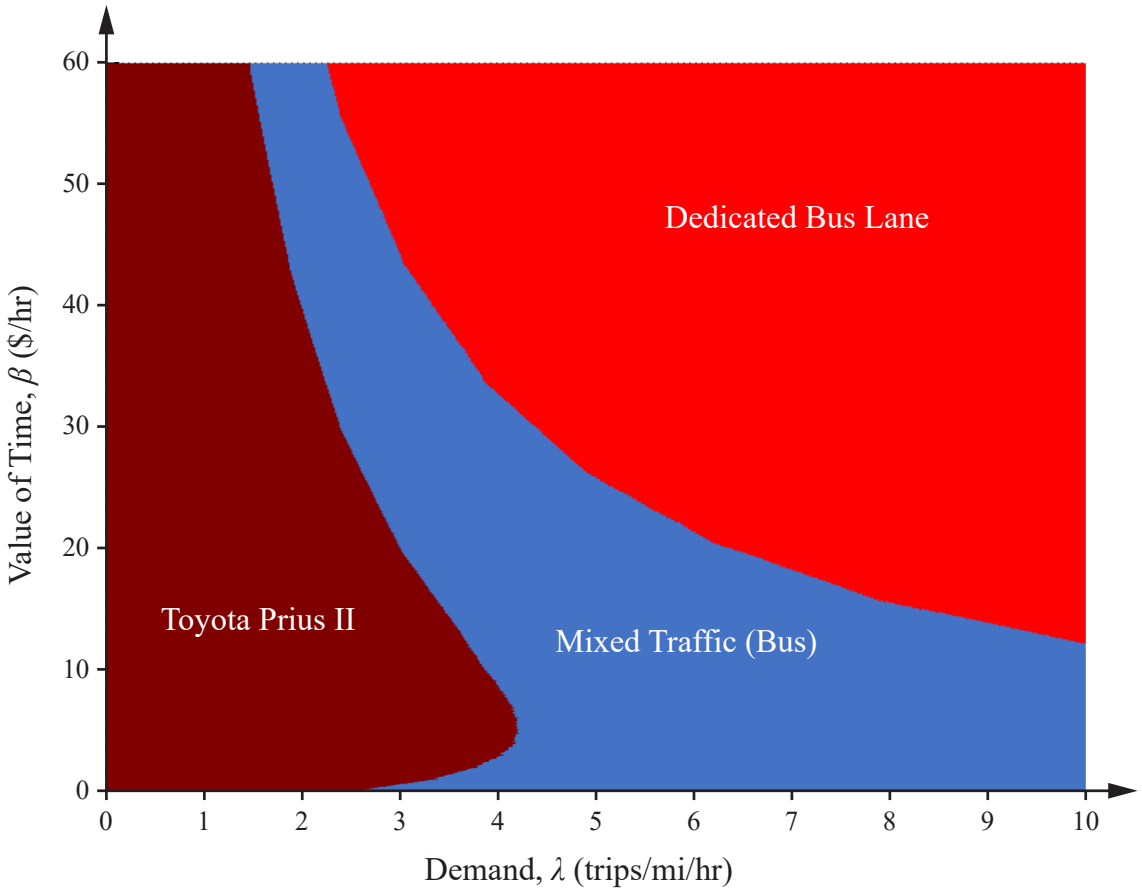


Figure 4.21. Most sustainable Transportation Modes with Low Demand Levels and Avg. Trip Length = 8 mi.

With the capital cost included in the operation cost of the trunk technologies, the following figures show the trade-offs among the modes and the mode that is the most cost-effective based on the three aspects of sustainability. Figure 4.22 compares the generalized values of transportation modes in this study. Based on Figure 4.22, when

the generalized value is low, the hybrid and DBL are the sustainable modes, and with a mid-value of the generalized cost, a mixed or a Full BRT is the cost-effective mode.

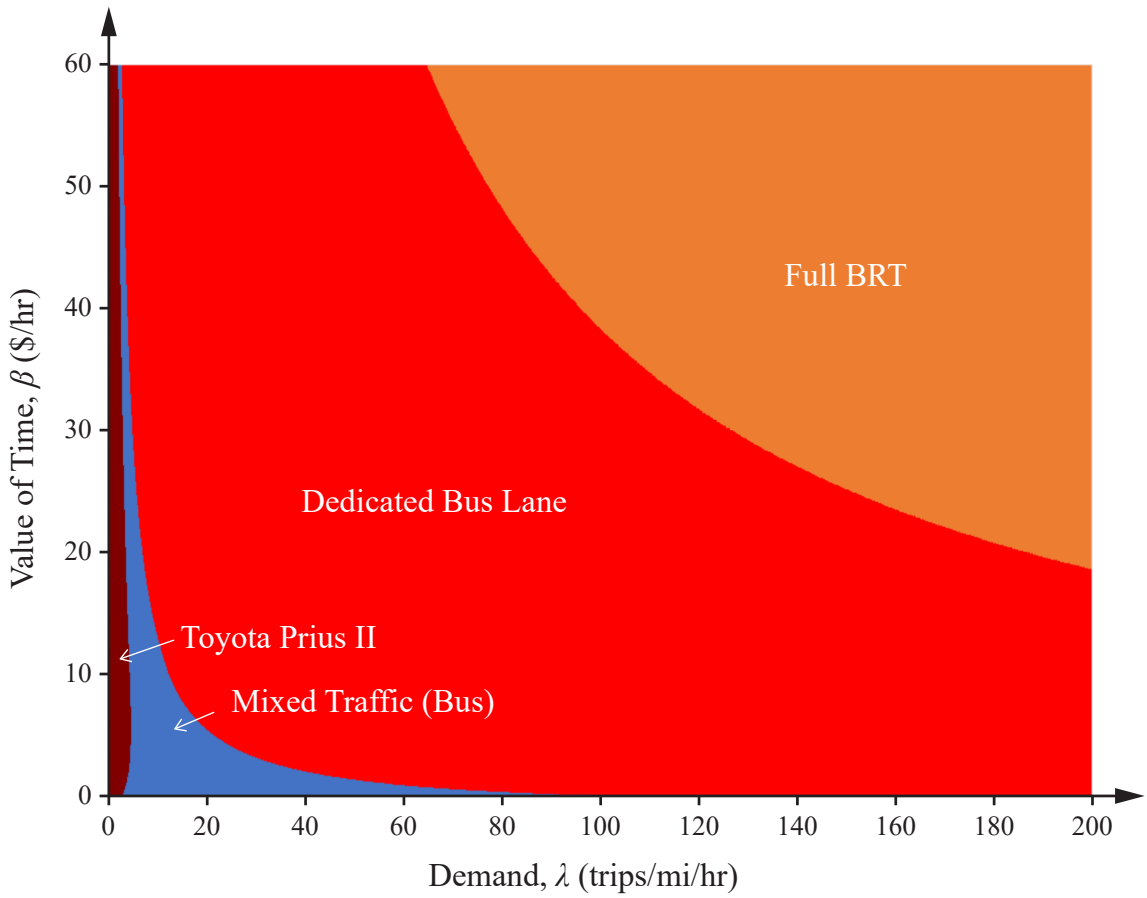


Figure 4.22. Trade-offs Among Sustainable Transportation Modes with Low Demand Levels and Avg Trip Length= 8 mi.

Figure 4.23 shows the modes that are the most competitive for cities with travelers who have the range of value of time, an average length of trip of 20 mile and level of demands that were used for this analysis.

4.10 Chapter Summary

Chapter 4 focused on showing how the sustainability framework developed in this study can be applied to existing real-world public transportation systems or routes to assist in the decision-making process to sustainably plan or design multi-

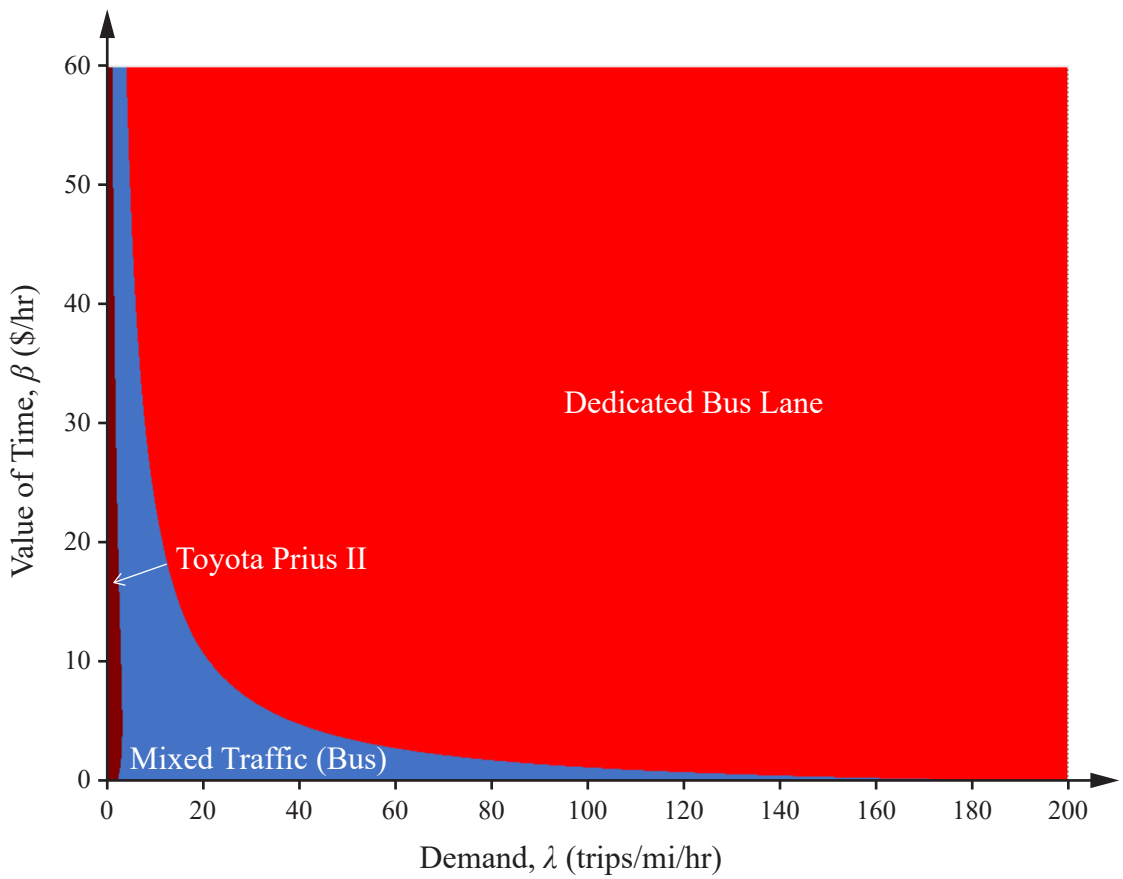


Figure 4.23. Most sustainable Transportation Modes with High Avg. Trip Length= 20 mi.

modal transportation routes. The case study that applied the approach in real cities identified the technology(ies) that best suited each city. The input variables were investigated to compare the one(s) that had the most impact on generalized cost.

Each of the trunk technologies investigated in this study were analyzed using sensitivity case scenarios to identify which of the transit attributes have the most impact on the transit design and operations, as well as the users. Lastly, the chapter investigated the effects on emissions of switching users to another mode of transportation. Pareto-frontier analyses were performed to minimize some of the three aspects of the sustainability concept using other aspects as constraints or characteristics that are important to current and potential transit users.

The findings in Figures 4.8 and 4.9 interpret the cost of moving passengers switching to public transportation. Based on these results, when the demand rate is very low, the generalized cost and the GHG emissions for hybrid vehicles is low, while with mid-demand rate value, the trade-offs among private vehicles and public transportation as the generalized cost for public transportation is higher compared to the GHG emissions is lower for public transit. Last, with a high demand rate along the corridor, the generalized cost for transit and GHG emissions are both lower compared to those of conventional and hybrid vehicles. All contour graphs show that as the decision variables decrease or increase, the generalized cost is impacted. But, the headway was found to the most important decision variable that decision makers should pay more attention to when planning and designing sustainable multi-modal transportation routes in a corridor.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Multi-Criteria Optimization

The findings of this study reveal several insights that can inform decision-making for transit agencies and other stakeholders. The following sections present the different analyses that were preformed to interpret the findings.

The second aspect of the decision-making tool explored how capital, operation, and maintenance cost (i.e., Agency Cost) plus the user travel cost (i.e., User Cost) can be minimized subject to the GHG emissions cost or CO_2e and vice versa. This part of the analysis was performed because some cities have set high bars to reduce GHG emissions as fast as possible, and therefore, stakeholders or practitioners might be willing to worsen the user travel time and/or the capital and operations and maintenance (O & M) costs to meet their objectives of reducing emissions. To show the trade-offs of the results of this analysis, Pareto frontier plots were created in Matlab.

5.2 Pareto-Frontier Analysis of all Trunk Technologies

The potential of multi-modal transportation in a city can have a number of impacts on the population of the city, the economic growth, and the environment. With more than one mode available to travelers, accessing different destinations in a city or zone might become easier. However, the decision making has become more complex for passengers, stakeholders, policy makers, and transit agencies. Hence, strategic frameworks or tools that can be used to ease the decision-making process are becoming

more appealing to the transportation professionals. Three cases of Pareto frontier were investigated to assist transportation decision makers when planning to operate one of the public transit technologies that were studied (e.g.,MT bus, DBL, tram, LRT,and MHR). When rails used offshore wind energy, the Pareto frontier findings were slightly different compared to coal energy.

5.3 Socio-Economic Cost Versus Greenhouse Gases Emissions

Assuming transit agencies set some constraints on the amount of GHG emissions, all available transportation modes were evaluated accordingly. The socio-economic cost of all available transportation modes in this study was minimized subject to the GHG emissions in gCO_2-equivalent to identify the modes that agencies should plan on operating to meet the GHG emissions constraints.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & AC(S,H) + UC(S,H) = \text{Social Economic Cost} \\ \text{subject to} \quad & E(S,H) \leq \text{Emissions Constraints} \\ & S, H \geq 0 \end{aligned} \tag{5.1}$$

According to Figure 5.1 when the GHG emissions restrictions are less than 100 gCO_2e per trip, the LRT-Coal and DBL modes are the most sustainable from a socio-economic standpoint,with trade-offs among all other public transit technologies in this study. As the GHG emissions restrictions increase and the socio-economic costs decrease, the MT and DBL socio-economic costs get closer to one another.

5.4 Agency Cost Versus Greenhouse Gases Emissions Constraint

Minimizing the agency cost of operating a transit mode can also affect the performance of the transit system, and as a result could push away travelers to switch to a

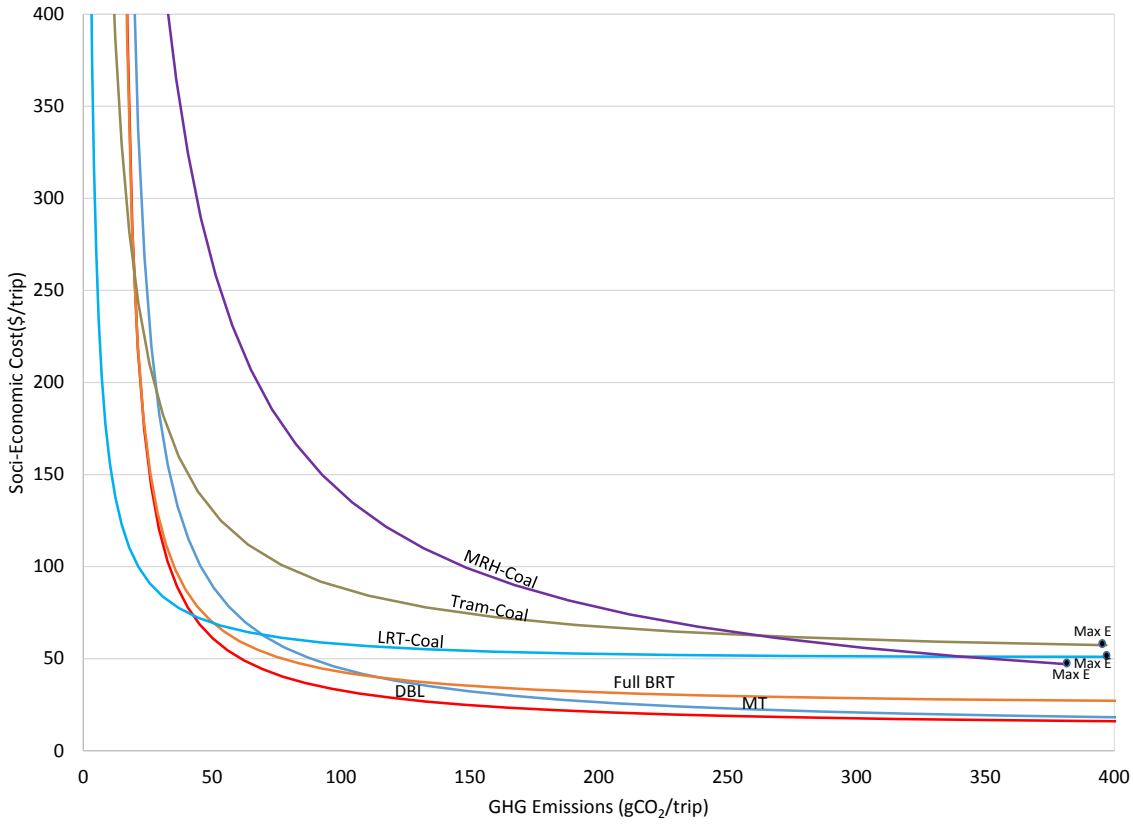


Figure 5.1. Pareto Frontier of Socio-Economic Cost of Transit Trunk Technology.

different mode. To investigate the Pareto frontier among all the transit trunk technologies that were evaluated in the corridor in regards to the agency cost and GHG emissions, the capital, operating, and maintenance costs, called agency cost in this study, were minimized subject to the GHG emissions. The findings from optimizing the agency cost subject to the GHG emissions cost show the Pareto frontier as points where trade-offs among the transit modes happened.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & \text{Agency Cost}(S,H) \\ \text{subject to} \quad & E(S,H) \leq \text{Emissions Constraints} \\ & S,H \geq 0 \end{aligned} \tag{5.2}$$

The findings in Figure 5.2 show that the Pareto frontier of all trunk technologies in this study is a linear line with trade-offs among all modes. In terms of decision making a mixed traffic bus, a dedicated bus lane, and full BRT are more cost effective compared to a light rail, tram, and metro heavy rail. But LRT-Coal is the mode with the lowest GHG constraints. However, decision makers might choose to select one of the other modes instead of a mixed-traffic bus if users' travel time is worsen.

5.5 Users Travel Time Cost Versus GHG Emissions Constraint

Minimizing the GHG emissions cost also has the potential to affect passengers' travel time. Hence, the user cost of travel was also minimized subject to the constraints on the GHG emissions, to avoid the risk of having passengers switch to more convenient modes due to the increase in travel time. Considering the effects of user cost on the overall success of multi-modal transportation systems, this study investigates the impacts of the GHG emissions on the user cost. According to the finding of the latter analysis, the results show that metro has the highest user cost as the

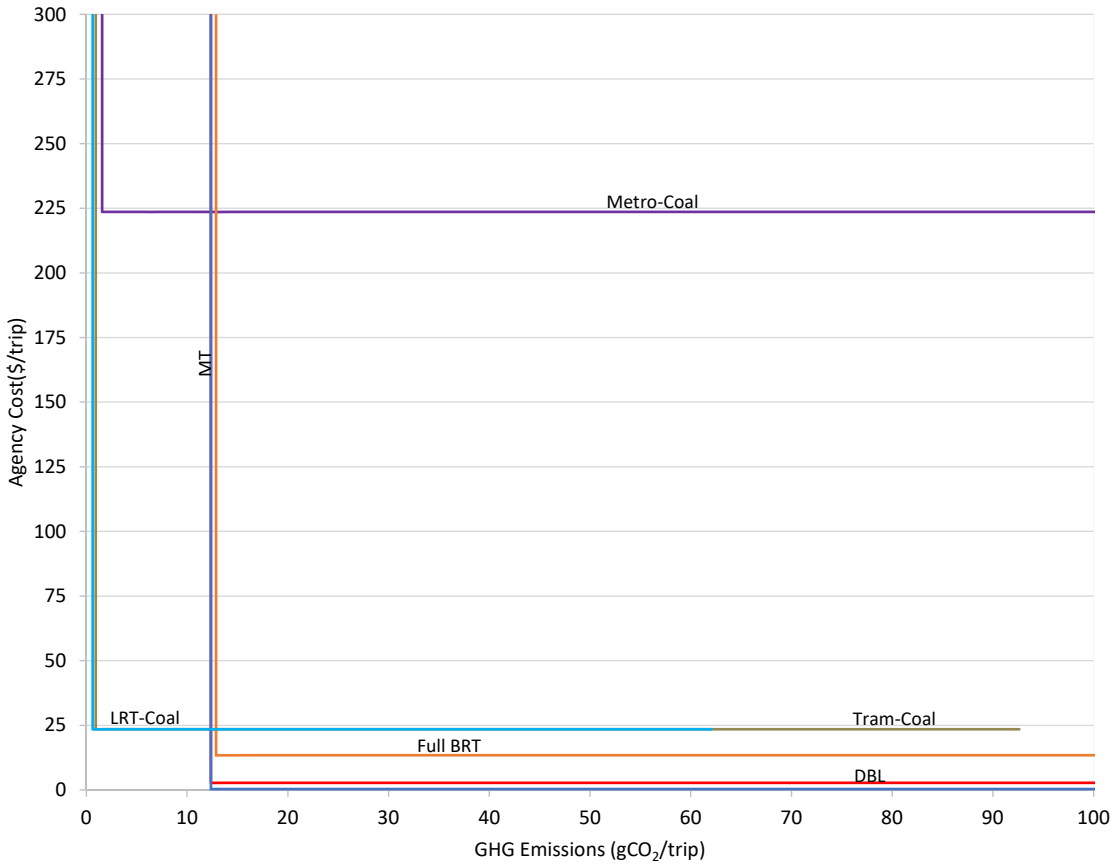


Figure 5.2. Pareto Frontier of Agency Cost of Transit Trunk Technology.

demand along the route increases. With low GHG emissions constraints a light rail trunk results to the lowest user cost. Trade-offs among the mixed, dedicate lane buses, full BRT, and metro happened at certain demand levels. Figure 5.3 shows the Pareto frontier among all transit modes along the corridor.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & \text{User Cost}(S,H) \\ \text{subject to} \quad & E(S,H) \leq \text{Emissions Constraints} \\ & S,H \geq 0 \end{aligned} \tag{5.3}$$

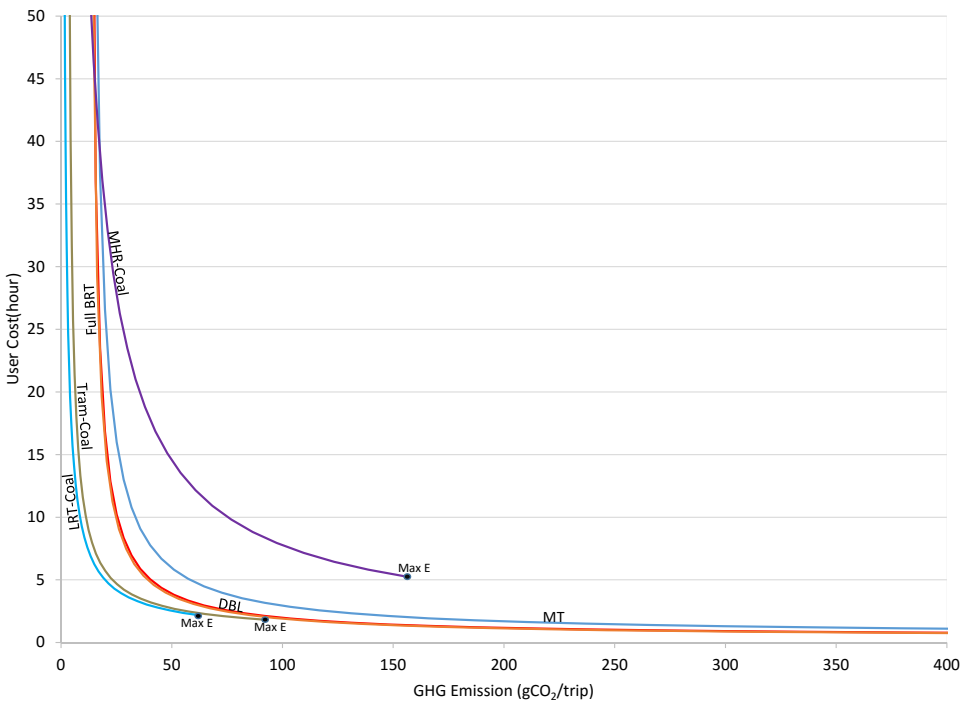


Figure 5.3. Pareto Frontier of User Cost of Transit Trunk Technology.

5.6 Comparison of Public Transportation and Private Vehicles

Making public transit the most competitive mode is always the ideal of transportation decision makers. Given the fact that some travelers are constantly switching until they find the most suitable mode of transportation to reach their destinations, the author also investigated the effect of travelers switching to private vehicles if their daily public transportation ride or experience was not satisfied. Hence, the GHG emissions were minimized subject to general transit cost less than or equal to private vehicle generalized cost. This section of the analysis optimizes the GHG emissions subject to the cost of the generalized cost transit less or equal to the generalized cost of private vehicles.

In this study two types of cars were included. The following analysis was performed to investigate how public transit modes can behave to compete with private vehicles. Similar to the analyses that were conducted to evaluate the trade-offs of all transit modes, one graph was plotted from the optimization results of each vehicle when the generalized cost of public transit is less than or equal to both vehicles generalized cost in the corridor. The following formulation was used to investigate how competitive public transit can be compared to private vehicles.

$$\begin{aligned} \underset{S,H}{\text{Minimize}} \quad & Emissions(S,H) \\ \text{subject to} \quad & GC_{\text{transit}}(S,H) \leq GC_{cars} \\ & S,H \geq 0 \end{aligned} \tag{5.4}$$

Figure 5.4 presents the results from the emissions of public transit while constraining the generalized cost of transit minus the generalized cost of the hybrid vehicle when rails use coal as fuel. This Figure shows that metro heavy rail is still the mode that produces the highest GHG emissions leading by the tram-Coal. But when the travel demand is within the range of 190-250 trips per mile per hour trade-offs were

identified among the LRT-Coal, Full BRT, and the DBL. LRT-Coal is shown as the most environmentally-friendly within the range of 190-250 level of demands.

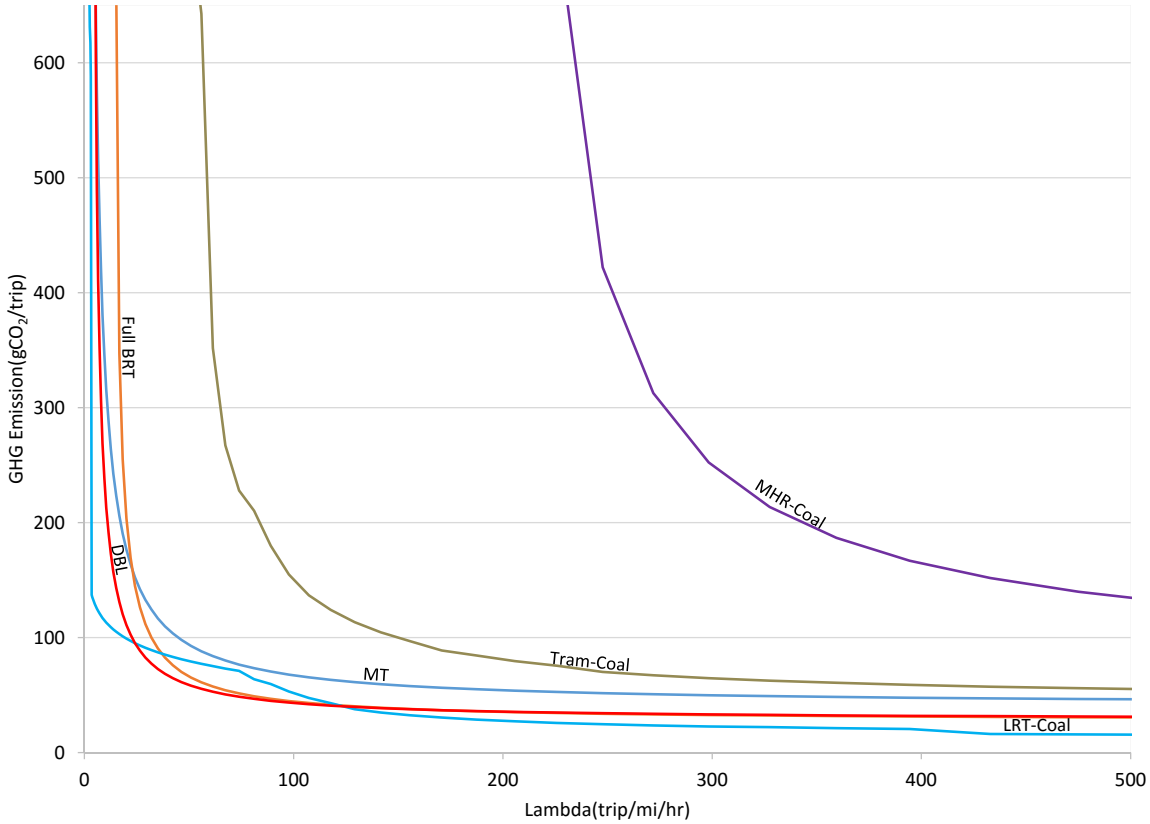


Figure 5.4. Optimum Emissions when Public Transit is Competitive with Hybrid Vehicles.

Figure 5.5 reveals that the optimum GHG emissions when public transit is more sustainable in regards to the environmental aspect of sustainability. The findings presents that LRT-Col remains the most eco-friendly. A MT bus was found to be most environmentally friendly than tan a full BRT and a tram-Coal.

Figure 5.6 shows that when transit is most cost effective than conventional vehicles, a full BRT is the most environmentally friendly with trade-offs at mid values of lambda. A tram also found better for the environment when the demand is high.

Figure 5.7 shows the findings of the generalized cost values of public transit when the GHG emissions were minimized while having the generalized cost of public transit

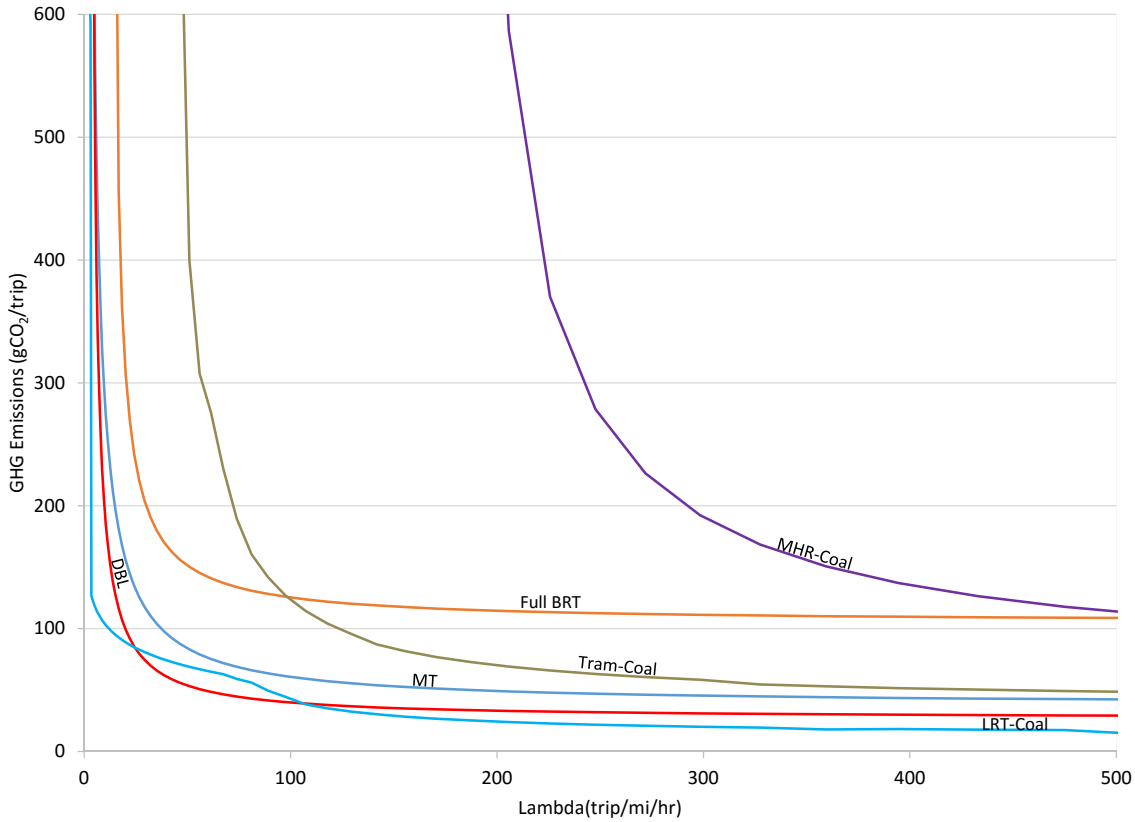


Figure 5.5. Optimum GHG Emissions based on Public Transit Competitiveness with ICE Vehicles.

cheaper than hybrid cars. When public transit cost is less than conventional vehicles, Full BRT was found to be the most cost effective mode when the demand is higher. At a certain level of demands, trade-offs happen among the MT bus, DBL, and Full bus rapid transit.

5.7 Case Studies of Showing Trade-offs in Real World Cities

To apply the model that was developed in this study, multiple case studies were selected to find the technologies that will best suit a city. To conduct the case studies, a number of cities were selected using the Millennium Cities Databased. The analysis also assisted in answering an important question that might appear to be very important to transit agencies. In other words, the analysis also aimed at showing

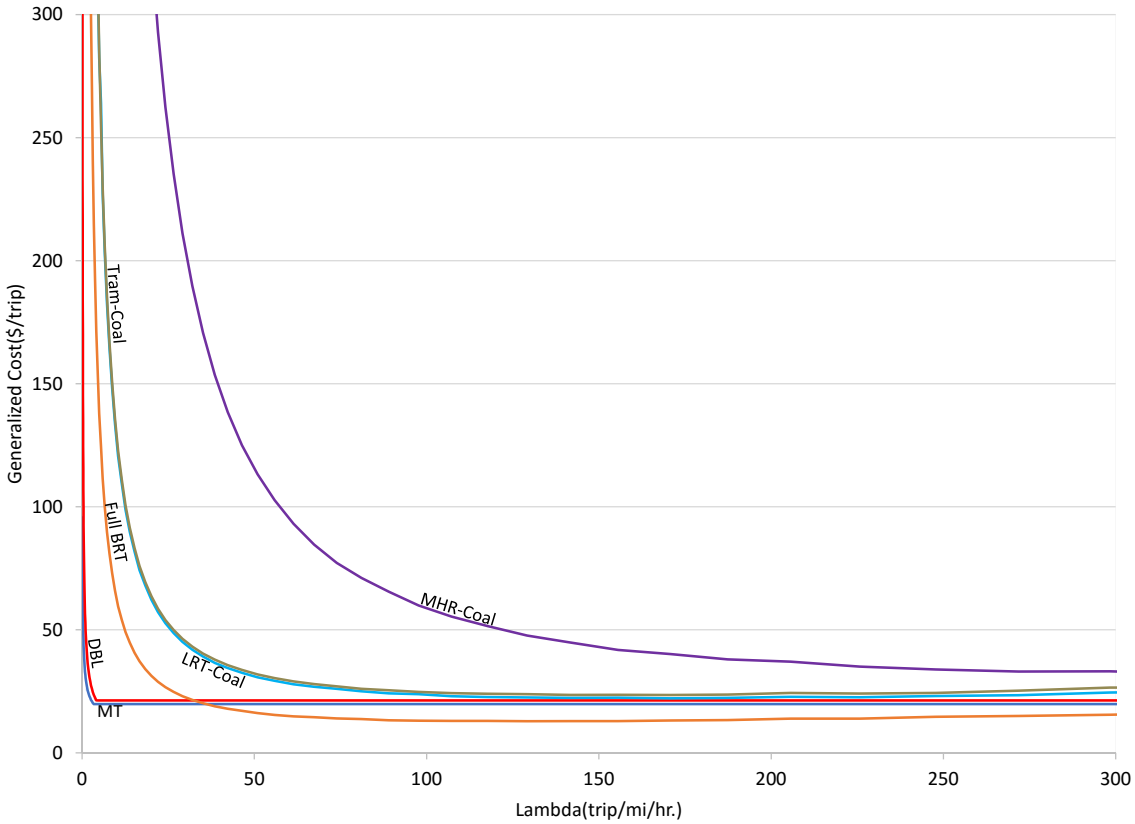


Figure 5.6. GC of Public Transit Competitiveness with ICE Vehicles.

at what level of demand rate a specific mode investigated in this study is warranted to meet the transit agencies' goals and mission statements of providing efficient modes of transportation to the population while simultaneously meeting all three aspects of sustainability.

The Pareto frontier concept, which has been used in several multi-criteria decision-making studies, was used to answer when a specific transit mode was needed to sustainably accommodate the population. Firstly, the author chose to optimize all three functions separately to show the trade-offs among each other. Next, the capital and operation and maintenance costs were minimized with the user travel time and the emissions costs as constraints. With the results of the optimizations, 3D surface plots were prepared to predict where each of those cities was located in the plots based on their average transportation demand and passenger value of time. Those figures

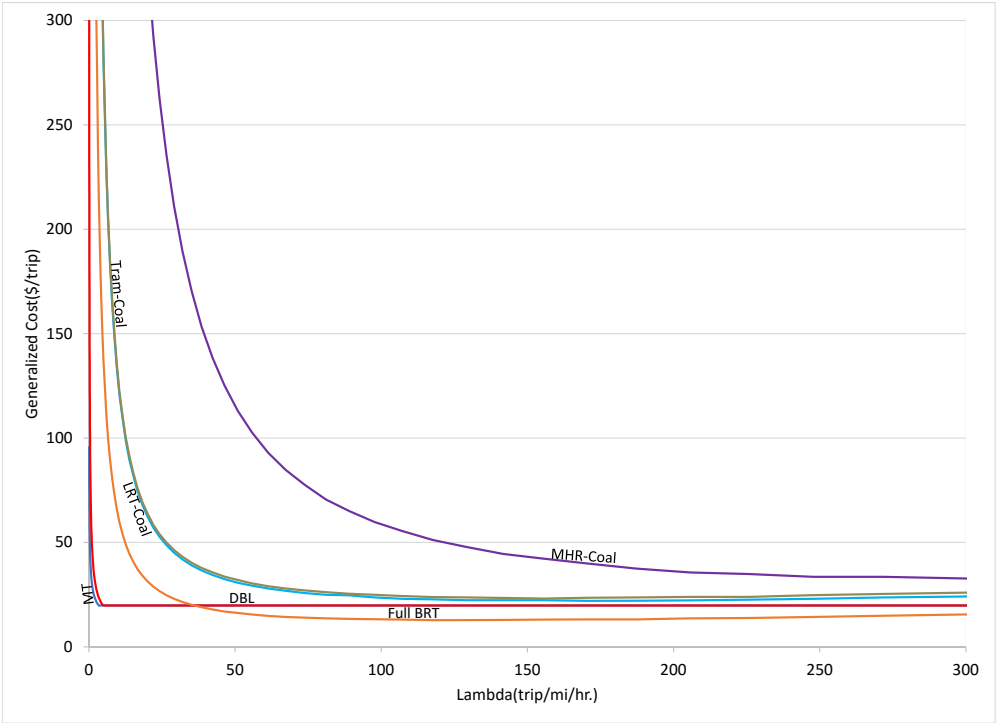


Figure 5.7. Optimum GC when Public Transit is Competitive with Hybrid Vehicles.

show each city and the technology that should be selected based on the objectives of the practitioners.

Figure 5.8 shows different cities around the world with their value of time and the average travel demand for public transportation. By calculating the average demand rate and the value of time of all passengers who have adopted public transportation as their daily modes in those cities, the approach proposed in this study was used to find the optimum modes that will be the most effective for each of those cities based on the GHG emissions, the agency cost, and the user travel cost. The data to perform the latter analysis was collected from the millennium database(Kain et al., 1992). Figure 5.8 shows the selected cities with the modes that were found to be the most cost effective in terms of generalized cost. Additionally, Table 5.1 compares

the modes that will be the most suitable for each study in terms total generalized cost and eco-friendly considering an homogeneous demand rate along a linear corridor with equal stop spacing.

For this analysis a 20 dollars per metric ton value of market price was used for the GHG emissions cost gamma(γ) subject to the stop spacing and headway to perform the optimization. In fact, if a greater γ value would have been used to reach the findings listed in Table 5.1, the decision making of selecting the most cost effective technology(ies) would not have been different since the cost of emissions was found to be the smallest within the generalized cost.

A case scenario of the generalized cost when a range of GHG emissions cost values were used. It was found that the magnitude of the emission findings of LRT and tram was found to be slightly different than previous findings that used higher or lower values of γ, without changing the decision. Although, in terms of GHG emissions, the findings for tram-Coal and LRT-Coal were found to be very close for several cities. That means, if a city does not have a constraint on the emissions, that city can either go with a tram or a light rail.

Focusing on the public health benefits of reducing GHG emissions, other pollutants as shown in Table 3.2 could have been investigated. It is true that in some countries a number of other GHG pollutants from the transportation sector have negatively impacted the human health. That implies that the transportation mode selection might perhaps be different compared to the findings shown in Table 5.1 for some countries if other pollutants that are listed in Table 3.2 in Chapter 3 were also investigated as the pollutants in the said table have higher weights compared to carbon dioxide. However, this study does not focus on evaluating direct public health benefits or impacts from planning and operating a sustainable mode of transportation so those listed pollutants were not further evaluated.

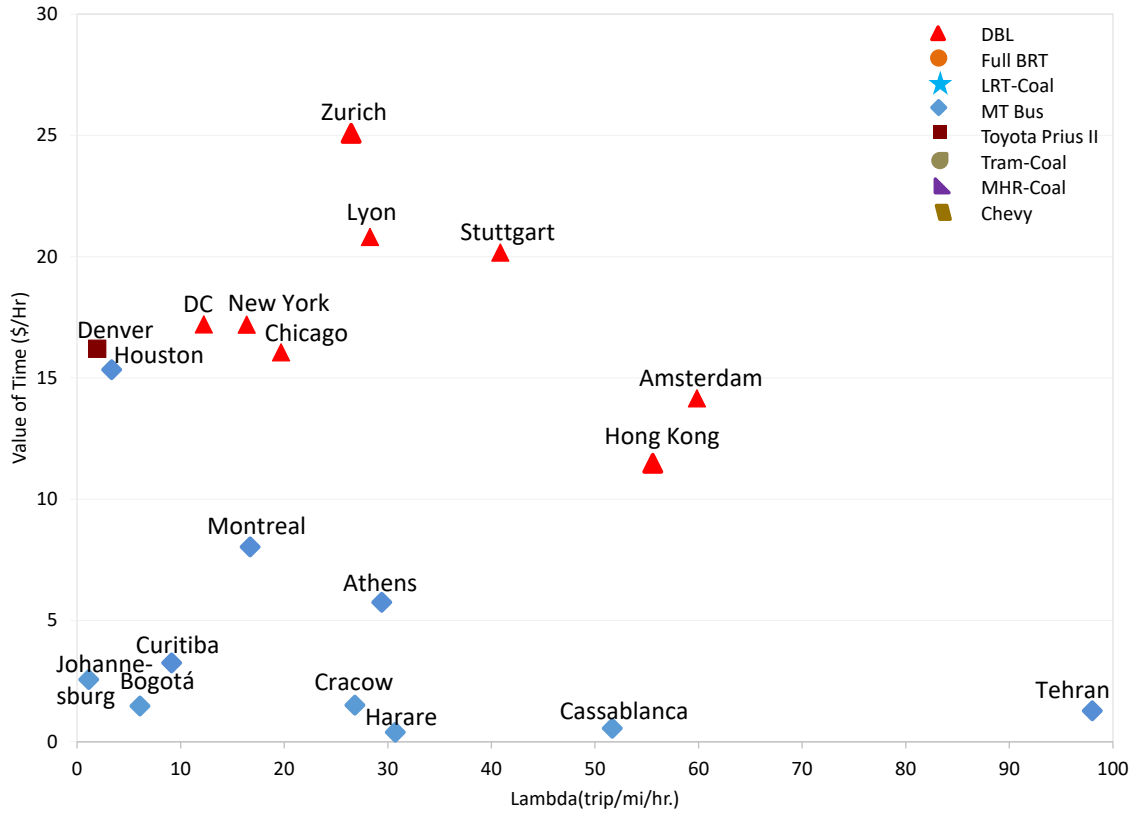


Figure 5.8. Decision-Making for Worldwide Selected Cities based on Generalized Cost.

Despite a number of trunk technologies that have been investigated in this study, not all of those trunks are suitable for a city as each of those cities have different sizes and number of people. Table 5.1 shows a comparison of different cities that were selected to apply the framework decision support model that was proposed in this study.

The findings presented in Table 5.1 show the case scenario of rails use coal as fuel. Table 5.1 shows that in the case that those cities would like to use this proposed model to plan and design sustainable mode with homogeneous demand, those modes listed under each city will be the sustainable modes based on the sustainability concept.

Examining the findings in table 5.1, the findings do not follow a similar pattern, but it can be concluded that when both demands and value of times are high, a DBL

or full BRT mode was found as the most cost effective. However, with cities that have high demands and low value of times, a MT bus was found to be the most cost effective. In terms of environmentally friendly, LRT-Coal was found to be the cleaner mode to plan and operate to emit less GHG CO_2-equivalent in the environment.

Table 5.1. Comparison of Different Cities with Cost Effective Transit Mode per City Case Study

Selected City	λ (trip/mi/hr)	β (\$/hr)	l (mi)	GC (\$/trip)	E (gCO_2/trip)
Denver, USA	1.95	16.19	6.82	Toyota Prius II	LRT
Stuttgart, Germany	40.86	20.17	3.32	DBL	LRT
Curitiba, Brazil	9.12	3.25	7.27	MT	LRT
Houston, USA	3.34	15.35	5.77	MT	LRT
Montreal, Canada	16.71	8.03	5.13	MT	LRT
Hong Kong, China	55.57	11.48	4.70	DBL	LRT
Amsterdam, Netherlands	59.84	14.16	2.93	DBL	LRT
Zurich, Switzerland	26.45	25.08	7.64	DBL	LRT
Tehran, Iran	98	1.28	3.83	MT	LRT
Athens, Greece	29.41	5.75	3.80	MT	LRT
Chicago, USA	19.69	16.05	6.53	DBL	LRT
New York, USA	16.38	17.20	7.54	DBL	LRT
Lyon, France	28.28	20.81	2.37	DBL	LRT
Washington DC, USA	12.24	17.21	6.61	DBL	LRT
Bogotà, Columbia	6.07	1.48	7.36	MT	LRT
Casablanca, Morroco	51.67	0.56	3.00	MT	LRT
Cracow,USA	26.81	1.51	3.54	MT	LRT
Harare, Zimbabwe	30.72	0.39	9.31	MT	LRT
Johannesburg, South Africa	1.14	2.57	21.55	MT	LRT

5.8 Chapter Summary

The analyses showing above in sections 5.1-5.7 reveal some valuable facts about transit characteristics, agencies, users, and decision makers. When planning or designing multi-modal transportation systems or routes, transit agencies and stakeholders have objectives that need to be met to plan an effective multi-modal transportation system that will be attractive to the public. The hope is that travelers who used to

adopt private vehicles to reach their daily destinations might switch to public transit or greener options of transportation. Transportation decision-making experts and policy makers can never be certain when selecting a technology will turn a city into a sustainable city with regards to accessibility and mobility. Figures 4.16, 4.19, 4.22, and 4.23 show that the length of trip of the passenger makes an impact on the decision making and trade-offs tipping points among the modes.

Chapters 4 and 5 explained some of the analyses that were performed to assist in comparing each mode to another and also interpret the findings based on the real world. Analyzing six trunk technologies and two private vehicles to decide the technology (ies) that meet all three E's of the sustainability concept required the author to separately explore each trunk when rails used different energy sources. The analyses presented in Chapters 4 and 5 are not the only ones that one should follow when evaluating different transit modes with private vehicles, but some are suitable to answer the objectives and questions that were asked in this study. The case studies that applied the approach in real cities identified the technology (ies) that best suit each city. The input variables were investigated to compare the one(s) that had the most impact on the generalized cost.

CHAPTER 6

CONCLUSION AND CONTRIBUTION

This chapter summarizes the findings for each aspect of sustainability and also explains how the contribution of the study can be applied to assist with multi-modal transportation decision-making.

6.1 Diesel Regular Buses (Mixed Traffic Bus and Dedicated Bus Lane)

Section 6.1 breaks down the findings of each transit trunk technology that was investigated in this study. The first part of this analysis explored optimal transit route design for a diesel regular bus (i.e., mixed traffic and DBL) with uniform stop spacing and no transfers. One of the aims of this study is to assist transit policy makers and agencies in minimizing operation and passenger time costs as well the cost of GHG emissions in terms of gCO_2e per trip. The costs for users, the agency, and emissions were modeled using continuous approximations in order to account for the three aspects of sustainability: social, economic, and environmental.

The results show the effect that optimum stop spacing and headway have on the general cost of the routes. The results in Chapter 4 show that there is an optimum stop spacing and headway that minimize the generalized cost. In reality, this means that with stops spaced farther apart and long headways, public transit users will experience greater generalized cost for using transit. These figures also show that among the two design variables, headway has a higher impact on the generalized cost. Additionally, the findings can also be explained based on user behavior, background,

and culture. However, the framework approach developed in this study prevents the investigation of users' or public transportation practitioners' behavior as well as decision-making uncertainty. Furthermore, another set of plots shows that the value of time, β, has significant impact on the sustainability of both types of bus routes, mixed traffic and dedicated lanes. An increase in β increases the average emissions per passenger. When β increases, a public agency has to provide enhanced service to continue attracting travelers if the demand rate is elastic. These findings were found to be same for each trunk technology evaluated in this research.

This research also determined that public transit is justified on the basis of generalized cost and GHG emissions cost compared to the two types of private vehicles. This finding raises policy questions that might force stakeholders and transit agencies to choose among the three aspects of sustainability or to switch to operating smaller buses or providing incentives to passengers to adopt low-emissions private vehicles. An analysis for buses and rails was performed to evaluate how much it will cost stakeholders to switch passengers to an environmentally cleaner mode of transportation. Another analysis that was performed also showed that increased passenger demand resulted in decreased travel time, agency cost, and emission cost per user for all public transit technologies.

A mixed-traffic bus was found to be the least costly in terms of capital, operations, and maintenance costs, with low demands and value of time. Furthermore, the results show that a mixed-traffic bus emitted less GHG emissions than a tram when electricity is generated from coal.

6.2 Full Bus Rapid Transit

A full BRT was also investigated in this study. The selection of this particular BRT was to look at the full potential of providing a sustainable BRT route, knowing from the literature review that a full BRT has been a favorable mode of selection for cities

in South America, United States, and in developing cities. Previous studies' findings publicized that a full BRT had the potential to assist in reducing CO_2 emissions within the transportation sector. One of the findings of this study shows that a full BRT's gCO_2 emissions per trip were lower than those of a MT bus, tram, Chevy Cavalier 2.2 L, Toyota Prius II, and MHR.

Based on the case scenario of β=\$15/hr., using the value of emission of \$20 per metric ton, the analysis used a range of λ as shown in Figure 4.16. It was noted that when the electricity of rail vehicles came from different sources such as burning coal, nuclear power, or offshore, the trade-offs among the modes were affected. In this study, tipping-point demands existed at which full BRT was associated with lower gCO_2e emissions per trip than Toyota Prius II, tram, LRT, DBL, and MT bus.

Based on the capital, operation, and maintenance costs, it was found that a full bus rapid transit is cheaper than a light rail, tram, or metro heavy rail with high demands. The trade-offs among the said costs were found when the level of demands was approximately 55 trips per mile per hour. For greater demands, MHR was found to be lower, until a demand of 70 trips per mile-hour. With regards to the generalized cost, the full BRT was also found to be cheaper than that of all transportation modes in this study with trade-offs among DBL. The generalized cost trade-offs among the Chevy and Prius II vehicles and full BRT happen when the demand rates were approximately 10 and 20 trips per mile per hour respectively.

Focusing on the social aspect of sustainability, a full bus rapid transit was found to be competitive with the users travel times with a bus operating in mixed-traffic. Indeed, the full bus rapid transit optimum headways were lower than those of a mixed-traffic route, but the fact that the number of passengers along the route was higher than that of a mixed-traffic bus, the full BRT might need to dwell longer for passengers to get on and off.

6.3 Light Rail Transit

Light rail transit is one of the transportation modes that is well known to have a lower impact on CO_2 emissions. The analysis of this study shows that CO_2 emissions per trip of light rail are lower compared to all other transportation modes in this study, namely tram, metro heavy rail, full BRT, DBL, and mixed-traffic trunk technologies, listed from higher CO_2 emissions to lower, respectively. The findings of this study have also revealed the same using a comparison of different energy sources.

The literature review identified light rail as a mode that suits suburban residents to increase ridership. In regards to light rail, another finding of this research demonstrated that the total capital and operations and maintenance (O & M) costs are greater than the capital and O & M costs of metro rail, whether the energy for LRT comes from coal, solar PV-utility, natural gas, nuclear, or wind/offshore. Since some of the input data were collected from previous research, perhaps those studies focused on light rail routes that were built in recent decades, which serve low-density areas. According to the literature review, light rail routes or systems that are built to accommodate low-density areas reduce the light rail capital costs because light rail construction can be done on existing ROWs.

Based on the user time, light rail was found to be in competition with metro when both gained their electricity from a coal power source. Tram travel time and gCO_2e of LRT were much closer to each other, but light rail emissions were always the lowest compared to the tram's at the specific demand rates that were investigated. The findings revealed that light rail had the lowest headway. Earlier, it was found that the headways have the highest impact on the generalized cost. Hence, decision makers with concerns of providing better headways to attract travelers might see light rail as the preferred choice compared to the other technologies.

6.4 Metro Heavy Rail Transit

The analyses of several energy sources to evaluate the technologies, which included a metro route, investigated several aspects to assist the MCDM process. In this research, optimized metro rail was found to have the highest number of passengers boarding per stop, with a higher stop spacing and shorter headways along the route. The O & M costs of the metro were lowest compared to those of light rail for a very high demand for each energy source investigated. The research found that the results can be representative of the real world, because at the beginning, the capital and O & M cost should be greater than those of a light rail route, because a metro requires more capital for the possible construction of tunnels. Additionally, for some cities, light rail is also known as a mode having a low number of passengers and high operating cost of passenger per mile. With more passengers boarding per stop for metro trunk, as one of the findings has indicated, more revenue can be gained, which might assist in paying the investment cost of the metro. Metro is known for use in wealthy cities, where the value of time is higher. In terms of generalized cost, a metro and the internal combustion engine (ICE) were found to be the most expensive, whether metro used a cleaner fuel or not.

6.5 Pareto-frontier Analysis of Sustainable Transit Trunk Technology

The Pareto-frontier analysis of all three aspects of the sustainability concept mentioned earlier in Chapter 5 was also evaluated using two different fuels for rails, such as coal,nuclear, or offshore wind energy. The analysis was conducted by optimizing each aspect of the sustainability concept subject to a range of constraints on GHG emissions. The findings of all analyses revealed not only that the magnitude of the findings changed when rails used offshore wind energy, but also the decision of mode selection was also modified. Further, the results show it is never necessary to emit

more GHGs than the emissions associated with minimizing the cost. This represents a maximum meaningful GHG emission constraint. Additionally, as the demand increases or decreases, the decision making also changes, with different trade-off points among all public transportation modes.

6.6 Comparison of Public Transportation and Light Duty Cars

The main goal of funding and improving public transportation is to motivate travelers to switch to a public transportation mode that is accessible to them and to meet the goal of reducing GHG pollutants in the environment. Transportation policies have used a number of strategies that appear to be cost-effective to reduce GHG and other health-related emissions effects. In this study, trade-offs were found among the Toyota Prius vehicle, and when the demand is low, adopting hybrid vehicles will emit less GHG emissions into the environment. Hence, this study investigated the cost of switching travelers to a cleaner mode of transportation. To reach the findings of this part of the analysis, the GHG emissions were minimized subject to the generalized cost of public transportation less than or equal to the generalized cost of both light duty private vehicles in this study. The analysis reveal that metro rail has the greater GHG emissions. Against the case of operating rails with a nuclear, or offshore wind power source, a full BRT was shown as the transit mode that has the highest GHG emissions per trip. Since LRT is the cleaner mode in terms of the environment, the results show that it will cost transportation decision-makers less money to switch travelers to adopt an LRT while more costly to switch to an MHR and the other modes in the order their GHG emissions were found.

6.7 Summary of Findings

Chapter 6 focuses on summarizing the findings of each trunk technology based on all three aspects of sustainability . Chapter 6 also identifies the trends in the findings and points out discrepancies and similarities of what previous studies related to this topic have found. Finally, the chapter provides explanations to accommodate readers when interpreting or applying the findings in the real world. Interpreting the findings of this study, each mode was found to be the best fit in a specific aspect that required the expertise of strategic decision-makers when planning or designing sustainable multimodal transportation routes in a corridor. However, the DBL and a full BRT, when an assumption of using existing ROW or spending on new infrastructure is used, were found to be the most cost-effective modes for cities, with trade-offs among these two modes. However, using heterogeneous demand, where the demand rate is constantly changing during the day, can require transit agencies to spend more on buying different sizes of vehicles or increase the vehicle numbers per hour. Doing the latter will increase agency costs of providing public transportation. That is when the strategy of regulating equitable incentives to users, with the hope of encouraging them to purchase hybrid vehicles or to use para-transit or Uber to quickly access transit stops or stations, comes into play. According to this research, light rail transit is the technology that can significantly reduce GHG emissions to assist in reaching global warming reduction goals, but because this study used cost data from previous studies that have focused on a wide range of cities, the agency cost of LRT was found to be higher compared to even an MHR route after a certain demand rate along the route. A mixed-traffic bus was also a good fit for the environmental aspect compared to a tram, but the user travel time would be affected by operating a tram, because it not only stops at traffic lights but also stops for passengers to alight and board. That implies transit agencies will still have to increase the service frequency, which

also has some negative impacts on the GHG emissions cost. The findings show that the MT has a higher frequency than a tram, despite its short stop spacing.

Using a cleaner fuel such as offshore wind energy for rails, the diesel buses and a tram were found to have greater CO_2-e emissions compared to LRT and MHR.

6.8 Research Contribution

The main contribution of this study is the formulation of a framework to plan and design multi-modal transportation routes that simultaneously optimize all three E's of sustainability (Economy, Equity, and Environment), as well as to account for the driving cycle components and impact on GHG emissions that occur from vehicles in a corridor. The optimization framework developed in this research may serve to assist transportation policy-makers, stakeholders, practitioners, and transit agencies in multi-criteria decision making. This research addresses the three aspects of sustainability and their relationship with transportation. Conducting sustainability analyses can be challenging and also requires a large amount of data to successfully evaluate the aspects of sustainability. Based on the nature of this research, one of its contributions can be positioned in the planning phase of providing sustainable multi-modal transportation routes to determine whether it is worth spending funds on data collection and weighting factors of the dimensions of sustainability. Hence, the sub-contributions of this research can be summarized as follows.

6.8.1 Economical: Costs and Profits

As previously mentioned, the theoretical contributions consist of developing models that account for all aspects of sustainability to guide transportation policy makers to regulate transportation issues when planning or designing more sustainable multi-modal transportation systems to accommodate the users. The methodological contribution is the development of a framework to quantify all dimensions into one

generalized cost for both transit technologies and private vehicles in the corridor. That implies that each of the three costs that compose generalized cost can be evaluated, weighed, and compared upfront to facilitate the decision-making process. The sensitivity of choosing one aspect over another can be balanced by other strategies, namely future transportation regulations, introduction of extra features to users, or buying smaller sizes of vehicles in the case of homogeneous demand along the route.

In terms of the economical aspect, the findings show that the agency cost is sensitive to gCO_2e, GHG emissions cost, and user cost. An increase or decrease in GHG cost, gCO_2e emissions cost, and/or user cost can affect the agency cost as well as diminish the profit of operating public transportation.

6.8.2 Equity/Social: User Cost

The effect of the equity aspect of sustainability depends on the quality of public transportation services as well as the service frequency of each trunk technology along the corridor. This research explored the modeling of transportation systems designed to serve users based on their value of time, length of trips, and the demand density along a corridor. This section of the modeling shows that as the cost of user time increased, the generalized cost also increased. Additionally, the vehicle capacity constraint was also met because the demand rate along the route was assumed to be constant. However, one of the limitations of this study was the fact that the findings were unable to predict when and how the user cost would be affected if the service frequency diminished.

6.8.3 Environmental: GHG Emissions Cost

Quantifying the GHG emissions cost in this study while taking into account all three operation modes, idling, cruising, and stopping of the driving cycle, made this study unique and also the newest contribution to this body of research. The latter contribution can be used to compare GHG emissions of modes that are operating

with the same characteristics, such as transit signal priority, dedicated right of way, and others. An example case in this study can be the findings of a GHG emissions of a DBL and an LRT. Despite both modes operating in their own right of way with transit signal priority, the findings revealed that an LRT is the most environmentally friendly. The emission factors for each of the driving cycle modes associated with DBL and LRT explained why an LRT emitted less emissions. With the growth of sustainable development, countries all over the world are in the process of applying sustainability's several disciplines and, most importantly, to projects that lie within the transportation sector. With the use of the VSP method, the emission factors for the emissions model can be calculated. The findings in Figure 3.5 and Table A.14 show the impact of each operation mode when driving in the real world. The acceleration and deceleration emissions factors and rates were found to be lower than those in the cruising phase. Lastly, the methodology of this study can be used to evaluate the Pareto efficient strategies when regulating environmental public transportation operations. A DBL was found to have a lower gCO_2e per trip than all other modes, except when an LRT's energy comes from natural gas, nuclear/wind offshore, or solar PV-utility.

At some point where the emissions are found to be the same for some modes at specific lambda values, transit agencies will need to focus on the Pareto frontier efficient strategy to evaluate the aspect that will worsen if one of the modes is selected over another. Scaling the importance of rejecting one aspect over the others should be undertaken to predict the impact of the decision. The emissions trade-off tipping points scan can also be useful when setting constraints on a CO_2 emissions equivalent for a potential mode in a corridor. Emissions tipping points for each trunk technology and private vehicles are summarized in Tables A.12 and A.13 in Appendix A.

Last but not least, unlike other related studies that focused their development framework optimization to sustainably plan or design multi-modal transportation,

this research developed a wide-ranging continuum approximation approach using idealized assumptions with the incorporation of constraints that affect passengers' behavior, such as vehicle capacity, user value of time, and others, in order to enable any city to apply this research methodology with the use of certain characteristics that fit that city, to ease their decision-making process in similar projects.

6.9 Concluding Comments

Accounting for sustainability when planning or designing multimodal transportation routes in a corridor to efficiently accommodate travelers can become a very complex problem, as neglecting one or more of the sustainability aspects impacts travelers, practitioners, and environmental and other entities that are in some way affected by the transportation sector. The findings of this study revealed that sustainable strategic decision models that were developed by researchers and practitioners can be reviewed to incorporate environmental regulations and social regulations to achieve sustainable decisions when trade-offs happen among the three E's of sustainability.

The approach proposed in this research is more realistic to sustainably plan or design efficient transportation with the ability to account for all phases in a vehicle driving cycle while concurrently evaluating all three E's of sustainability. The framework of this approach is general and can be adopted for any type of city that has or wishes to plan or redesign a trunk technology route. The use of this method will enable stakeholders and transit agencies to economically save on data collection or construction cost to select the most appropriate technology for a city. However, the model does not account for uncertainty when strategy decisions are made when trade-offs happen between private vehicles and other transit modes.

Part of this research investigated multi-criteria decision-making for design of a multimodal corridor, and it included a comparison of one conventional and one hybrid

vehicle, based on all three aspects of sustainability of two regular buses, with one operating in mixed traffic and the other operating in ROW Category B. Using Matlab, the optimization showed that at some points, more precisely after a demand rate of approximately three trips per mile-hour, based on an environmental regulation, policy makers should provide an equitable incentive to attract more users to purchase hybrid vehicles if reducing gCO_2e emissions per trip is the top priority of the city. However, if the transit agencies are willing to lower the travel time of users, another strategy decision can be to operate smaller buses. The latter strategy will work where demand is homogeneous and might not work with a heterogeneous demand rate along the line. Lastly, comparing the mixed-traffic bus with DBL, it was also found that DBL is more cost-effective when it comes to operation and maintenance as well as reducing gCO_2e per trip.

A second part of this research applied the approach in this study to real-world cities. A number of cities around the world were selected. The overall total transportation demand rates and the average value of time of the travelers in each city were calculated using the Millennium Cities Database (Kenworthy and Laube, 2001). Based on an overall range of the latter demand rates and value of times of the passengers living in those cities, 3D plots for each trunk technology studied in this research were plotted to create a sustainable generalized cost matrix. Applying the latter decision tool, a suitable technology was found for each city. Additionally, specific headways and stop spacing were used to plot contour graphs to find the best decision variables for those real-world cities. The final findings of the second article may assist in the MCDM process to choose the mode that should be planned or designed for a city. Trade-offs happened among hybrid vehicles with all modes at different levels of tipping points. In some cases, more than one mode was found for a particular city. Again, DBL appeared to be the dominant mode based on generalized cost when the level of demands is less than 250 trips per mile per hour, while full BRT was found to

be the most user cost efficient, and LRT was found to be the most environmentally friendly.

A third part of the research focused on the Pareto frontier with multiple objective functions and constraints. Each mode was evaluated using 2D graphs, applying different assumptions to see the impact on generalized cost.

A number of insights can be of good use to policy makers, stakeholders, and transit agencies, as well as travelers who are conscious of one of the sustainability concepts when making decisions on selection of a daily transportation mode. Summarizing the environmental aspect of this study, it can be interpreted that the sources of energy consumption for rails and the cruising speed have significant impact on the emissions of each of the technologies studied in this research. In terms of generalized cost comparisons, DBL was found to be the most cost-effective mode after a demand rate of five trips per mile-hour, when the author assumed that infrastructure already existed. If infrastructure cost was included in the modeling framework, full BRT was found to be the most cost-effective mode. Light rail was found to be the mode with less gCO_2e emissions. However, when rail energy sources were changed, trade-offs happened at some specific demand rates.

To conclude, the main takeaway of this study is that full BRT is not always required, because DBL also has the potential to operate as a full BRT while satisfying the occupancy rate constraint. The gCO_2e emissions per trip were found to have the most impact on the user cost, because the results show that when the cost of GHG emissions reached $150 per metric ton, the number of vehicles along the route was diminished. However, the GHG market value does impact the decision making. A strategy to continue attracting more passengers would be for transit agencies to offer additional features at the stops or stations, as well as in-vehicle features to balance the extra waiting time of transit users. Furthermore, the environmental cost was found to be the smallest cost among the other two costs of the sustainability concept.

Finally, this model allows for systematic analysis of the effects of decision variables on each of the component costs. The methods presented in this study provide a framework for systematic analysis of emissions and systems costs associated with transit systems. By appropriately adjusting the input parameter values, the method can be applied to transit lines and private vehicles all over the world.

To answer the questions that were asked in this study, the GHG emissions cost was found to be the lowest cost compared to user and agency costs. However, the author can argue that the latter findings depend on the types of GHG pollutants and the location where the routes are operating. Because the other pollutants converting factors as shown in Table 3.2 in chapter 3 are higher, the emissions value will also be higher, which will result in a higher GHG emissions cost. Last, since the gram CO_2e emissions were found to simply change the magnitude of the findings,but not the decisions for selecting a trunk technology for cities with low or high demands, one can conclude that the generalized cost of sustainable multimodal transportation in a corridor can be modeled without account for the cost of GHG emissions.

The level of demand where DBL is warranted was found to be different for each case scenario when rail fuel comes from different power plants. Tables A.12 and A.13 showing each scenario, are available in Appendix A.

Compared to previous related studies' findings that BRT is the most efficient mode, this research, which accounts for all three driving cycles in addition to optimizing the generalized cost of public transportation technologies with private cars in a non-congestion traffic case, reveals that a DBL, as defined in this study, is the most sustainable mode with trade-offs among BRT when approximately 200 trips per hour per mile demand levels.

6.10 Future Directions

This research has some limitations which the author plans to continue exploring in the near future. Hence, to overcome the limitations of this approach, the following studies that are ongoing and will continue to explore all aspects of this study topic are as follows.

1. *What incentives are needed to get travelers to use the most efficient mode or modes identified in Aim 2?*

One of the findings in this research indicated that hybrid vehicles are more energy efficient than some of the technologies at some specific demand rate tipping points. Imagining a city that has heterogeneous demand or high value of times, environmental policy makers should regulate an equitable incentive that attracts travelers by enabling them to purchase hybrid vehicles. Hybrid vehicles are also known to have disadvantages, but there an alternative that removes some single more polluting private vehicles off the road. Then, policymakers need to work in conjunction with transit and para-transit agencies, Uber, Lyft, and Zipcars to determine equitable incentives for using environmentally friendly modes to support the global warming goal of diminishing GHG emissions.

2. *How do the results of this study change traffic conditions are dynamic?*

The sustainability development framework in this research assumed a static traffic flow scenario, even when more vehicles were added on the road. However, when traffic is congested, what are the effects on each dimension, and how much of a difference is made, as compared to the static model case scenario used in this study? Practitioners and transit agencies with mega cities that are most often congested can rely also on that framework to find the most suitable technology.

3. *What are the effects of uncertainty decision making when trade-offs happen among all three E's of sustainability?*

Planning or designing sustainable multi-modal transportation routes or systems seems very challenging. Stakeholders and transit agencies will have to prioritize one aspect over the others. For some countries, sustainability development has been fully accepted, perhaps because the populace has been fully educated on the concept and will not have doubts when selecting one aspect over the other.

The Appendix sections contains all tables that breakdown the cost data that was collected for this research. Additionally, the appendix sections also contain the emissions data that was calculated based on the three aspects of the sustainability concept to optimize the generalized function. The Appendix is separated in two sub-sections. Section A of the appendix has has all the data for all transit trunk technologies that were investigated in this study. Section B of the Appendix contains all data for the private automobiles that were compared with the transit modes to show the trade-offs among all sustainability aspects to ease decision-making process of the transit agencies and stakeholders. Furthermore, public transit and private automobiles findings are also shown in Appendices A and B, respectively.

APPENDIX A

TRANSIT MODEL PARAMETERS TABLES

Table A.1. Diesel Regular Buses Model Parameters (typical values used for this analysis)

Parameter	Symbol	Units	MT	DBL	BRT
Cycle Time Length	C	hour	0.01667	0.01667	0.01667
Average Trip Length	l	mile	8.1	8.1	8.1
Length of the Route	L	mile	20	20	20
Cost of Vehicle per Stopping	c_s	\$/stop	0.1	0.1	0.1
Cost of Vehicle per Distance	c_d	\$/veh-mi	1.609	1.609	1.92
Cost of Vehicle per Time	c_t	\$/veh-hr	78	78	100
Access Time	v_a	mi/hr	3.1	3.1	3.1
Commercial Speed	v_t	mi/hr	19.263	19.263	31.068
Free-Flow Speed	v_f	mi/hr	27.962	27.962	40.389
Loss Time per Stop	τ_s	hr/stop	0.001736	0.001736	0.01111
Dwell Time	τ_d	hr/trip	0.0014	0.0014	0.0014

Table A.2. Rail Trunk Technology Model Parameters (typical values used for this analysis)

Parameter	Symbol	Units	Tram	LRT	MHR
Cycle Time Length	C	hour	0.01667	0.01667	0.01667
Average Trip Length	l	mile	8.1	8.1	8.1
Length of the Route	L	mile	20	20	20
AC of Vehicle per Stopping	c_s	\$/stop	0.1	0.1	0.1
AC of Vehicle per Distance	c_d	\$/veh-mi	1.92	1.92	2.16
AC of Vehicle per Time	c_t	\$/veh-hr	100	100	100
Access Time	v_a	mi/hr	3.1	3.1	3.1
Commercial Speed	v_t	mi/hr	31.068	31.068	65.138
Free-Flow Speed	v_f	mi/hr	27.962	27.962	40.389
Loss Time per Stop	τ_s	hr/stop	0.001736	0.001736	0.01111
Dwell Time	τ_d	hr/trip	0.0014	0.0014	0.0014

Table A.3. Calculated Emission Factors for Diesel Buses Driving Modes using VSP Method

Operating Mode	Units	MT	DBL	BRT
Cruising, EF_c	(gCO_2 per hr)	28,684	28,684	28,684
Idling, EF_i	(gCO_2 per hr)	8,821	8,821	8,821
Stopping, EF_s	(gCO_2 per stop)	161	150	183

Table A.4 shows the cost parameters that were used to run the optimization for the two diesel regular buses in this study.

The Following table shows the cost parameters for the full BRT in this study.

Table A.9 below shows the sensitivity analysis that was performed using the acceleration and deceleration that that was assumed for the buses in this dissertation.

Table A.10 shows the results that were obtained from the sensitivity case scenario of full BRT.

Table A.10 shows the results that were obtained from the sensitivity case scenario of full BRT.

Table A.15 shows the results of the 20% change sensitivity analysis to investigate the impacts of rails emissions factors on the generalized cost. Those findings can be use to plot tornado graphs to graphically show the impacts and identify the rails GHG emissions factor(s) that has the most impact on the generalized cost.

Table A.4. Regular Bus Cost Parameter Breakdown

Parameter	Value	Units	Comments
Infrastructure Costs			
Infrastructure Line Cost	1,600,000	$/mile	Based on Kain et al. (1992) infrastructure cost in 1989 $
Infrastructure Line Cost	4,101,287	$/mile	Infrastructure cost in 2016 $ using Eq. 3
Infrastructure Line Cost, c_i^{DBL}	26	$/mi-hr	Assume the cost per station/stop is one-tenth the cost of the BRT station.
Infrastructure Station Cost, $c_s t$	0.6	$/sta-hr	Assume an amortization across a 30-year life span, with operation 350 days/yr. and 18 hr./day
Infrastructure Line Cost, c_i^{MT}	2.19	$/mi-hr	From Gonzales (2011)
Operation Costs (Distance)			
Infrastructure Line Cost	1,600,000	$/mile	Based on Kain et al. (1992) Maintenance Cost per veh-mi
	0.20	$/car-mi	From Sivakumaran et al. (2014)
Fuel Price per Gallon	2.384	$/gal	Based on national avg gas price, gasprices.aaa.com, last accessed Nov. 23, 2016
Fuel Efficiency	6	mi/gal	From Clark et al. (2007)
Cost per veh-mi	0.397	$/veh-mi	
Cost per veh-mi	0.597	$/veh-mi	
Cost per veh-mi, c_d^{Bus}	0.850	$/veh-mi	Accounting for inflation, converted to 2016 $
Operation Costs (Time)			
Labor Cost per Hour, c_t	60	$/hr	From Sivakumaran et al. (2014)
Purchase Price of Vehicle	290,000	$	Estimated average based on Hallmark et al. (2012); 40 ft. bus
Vehicle Lifespan	25	yrs	
Depreciation per Hour	1.84	$/hr.	Assume straight-line depreciation
Cost per Veh-hour, c_v	61.84	$/veh-hr.	

Table A.5. Full BRT Cost Parameter Breakdown

Parameter	Value	Units	Comments
Infrastructure Costs			
Infrastructure Line Cost	12,100,000	$/mile	Based on Boston Silver Line infrastructure cost in 2002 $
Infrastructure Line Cost	20,953,285	$/mile	Infrastructure cost in 2016 $ using Eq. 3
Infrastructure Station Cost, $c_{sta}^{FullBRT}$	26	$/mi-hr	Assume an amortization across a 25-year life span, with operation 350 days/yr. and 18 hr./day.
Infrastructure Station Cost, c_{sta}	500,000	$/sta-hr	Infrastructure cost in 2001 $ from Sivakumaran et al. (2014)
Infrastructure Station Cost, $c_{sta}^{FullBRT}$	900,471	$/sta	Infrastructure cost in 2016 $ using Eq. 3
Infrastructure Station Cost, $c_{sta}^{FullBRT}$	6	$/sta-hr	Assume an amortization across a 30-year life span, with operation 350 days/yr. and 18 hr./day
Operation Costs (Distance)			
Maintenance Cost per VM	0.30	$/car-mi	From Sivakumaran et al. (2014)
Fuel Price per Gallon	2.384	$/gal	Based on national avg gas price, gasprices.aaa.com, last accessed Nov. 23, 2016
Fuel Efficiency	6	mi/gal	From Clark et al. (2007)
Cost per veh-mi	0.397	$/veh-mi	
Cost per veh-mi	0.697	$/veh-mi	
Cost per veh-mi, $c_d^{FullBRT}$	0.99	$/veh-mi	Accounting for inflation, converted to 2016 $
Operation Costs (Time)			
Labor Cost per Hour, c_t	60	$/hr	From Sivakumaran et al. (2014)
Purchase Price of Vehicle	700,000	$	Estimated average based on Transit (2001); Janić (2011) articulated 60 ft. bus
Vehicle Lifespan	25	yrs	
Depreciation per Hour	4.444	$/hr.	Assume straight-line depreciation
Cost per Veh-hour, c_v	84.444	$/veh-hr.	

Table A.6. Tram and LRT Cost Parameter Breakdown

Parameter	Value	Units	Comments
Infrastructure Costs			
Infrastructure Line Cost	34,600,907	$/mile	Based on Janić (2011) infrastructure cost in 2010 $
Infrastructure Line Cost	43,781,185	$/mile	Infrastructure cost in 2016 $ using Eq. 3
$C_i^{Tram/LRT}$ - Infrastructure Line Cost	232	$/mi-hr	Assume an amortization across a 30-year life span, with operation 350 days/yr. and 18 hr./day
Infrastructure Station Cost, c_st	30,000,000	$/sta-hr	$0.5-9 M Infrastructure cost from Danaher (2009); Hsu (2005); Associates and Levinson (2007)
Infrastructure Station Cost	63,145,559	$/sta-hr	Infrastructure Cost in 2016 $ using Eq. 3
C_sta-Infrastructure Station Cost	334	$/sta-hr	Assume an amortization across a 30-year life span, with operation 350 days/yr. and 18 hr./day
Operation Costs (Distance)			
Energy Cost per Car	3.2	kWh/car-mi	Based on ATOC 05/06 Data March (2007)
Energy Consumption per Train	19.2	kWh/train-mi	Assume 6-car train
Average Energy Cost	0.1	$/kWh-hr	Electric Power Monthly Report year 2011
Energy Cost per Veh-mi	1.92	$/veh-mi	From Clark et al. (2007)
$C_d^{Tram/LRT}$ - Cost per Veh-mi	1.92	$/veh-mi	
Operation Costs (Time)			
C_t-Labor Cost per Hour	100	$/hr	From Sivakumaran et al. (2014)
Purchase Price of Vehicle	12,000,000	$	Estimated Average based on Wilson (2010) for 6-car-trains
Vehicle Lifespan	30	yrs	
Depreciation per Hour	64	$/hr.	Assume straight-line depreciation
S_m-Cost per Veh-hour	164	$/veh-hr.	

Table A.7. MHR/RRT Cost Parameter Breakdown

Parameter	Value	Units	Comments
Infrastructure Costs			
Infrastructure Line Cost	225,308,230	$/mile	Based on Fox et al. (2000) infrastructure cost in 2000 $
Infrastructure Line Cost	421,998,089	$/mile	Infrastructure cost in 2016 $ using Eq. 3
C_i^{MHR} - Infrastructure Line Cost	2233	$/mi-hr	Assume an amortization across a 30-year life span, with operation 350 days/yr. and 18 hr./day
Infrastructure Station Cost, c_st	74,500,000	$/sta-hr	Infrastructure cost in 2016 $ based on BART Extension
C_sta-Infrastructure Station Cost	394	$/sta-hr	Assume an amortization across a 30-year life span, with operation 350 days/yr. and 18 hr./day
Operation Costs (Distance)			
Energy Cost per Car	3.6	kWh/car-mi	Based on BART Systems Energy Consumption ASSESSMENT (2007)
Energy Consumption per Train	21.6	kWh/train-mi	Assume 6-car train
Average Energy Cost	0.1	$/kWh-hr	Electric Power Monthly Report year 2011
Energy Cost per Veh-mi	2.16	$/veh-mi	From Clark et al. (2007)
C_d^{MHR} - Cost per Veh-mi	2.16	$/veh-mi	
Operation Costs (Time)			
C_t-Labor Cost per Hour	100	$/hr	From Sivakumaran et al. (2014)
Purchase Price of Vehicle	15,000,000	$	Estimated Average based on Wilson (2010) for 6-car-trains
Vehicle Lifespan	30	yrs	
Depreciation per Hour	79	$/hr.	Assume straight-line depreciation
S_m-Cost per Veh-hour	179	$/veh-hr.	

Table A.8. Sensitivity of Regular Buses-Mixed Traffic and DBL General Cost of Transit (dollars/trip)

Variable	Variable Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Buses in Mixed Traffic						
Lambda(trip/mi/hr)	8	10	12	15.082	14.389	13.882
Beta ($/hr)	12	15	18	12.766	14.389	16.565
Gamma($/metric ton)	16	20	24	14.385	14.389	14.394
Accel./Decel.(m/sec^2)	1.6	2	2.4	14.391	14.389	14.389
Buses in Dedicated Lanes						
Lambda(trip/mi/hr)	8	10	12	13.560	12.950	12.505
Beta($/hr)	12	15	18	11.479	12.950	14.906
Gamma($/metric ton)	16	20	24	12.947	12.950	12.954
Accel./Decel.(m/sec^2)	1.6	2	2.4	12.9505	12.950	12.949

Table A.9. Sensitivity of Regular Buses-Mixed Traffic and DBL General Cost of Transit (dollars/trip)

Variable	Variable Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Buses in Mixed Traffic						
Lambda(trip/mi/hr)	8	10	12	15.082	14.389	13.882
Beta($/hr)	12	15	18	12.766	14.389	16.565
Gamma($/metric ton)	16	20	24	14.385	14.389	14.394
Accel./Decel.(m/sec^2)	0.8	1	1.2	14.390	14.389	14.388
Buses in Dedicated Lanes						
Lambda(trip/mi/hr)	8	10	12	13.566	12.950	12.505
Beta($/hr)	12	15	18	14.479	12.950	14.906
Gamma($/metric ton)	16	20	24	12.947	12.950	12.954
Accel./Decel.(m/sec^2)	0.8	1	1.2	12.951	12.950	12.950

Table A.10. Sensitivity of Full BRT General Cost of Transit (dollars/trip)

Variable	Variable Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Buses in Mixed Traffic						
Lambda(trip/mi/hr)	8	10	12	22.043	21.403	20.954
Beta($/hr)	12	15	18	18.156	21.403	24.566
Gamma($/metric ton)	16	20	24	21.399	21.403	21.408
Accel./Decel.(m/sec^2)	0.77/1.03	0.96/1.72	1.15/2.06	21.407	21.403	21.407
V_cr(m/sec)	38.4	48	57.6	21.406	21.403	21.409

Table A.11. Full BRT GHG Emissions 20% Change. Capture the Effects of Generalized Cost

Parameter	Parameter Value			Generalized Cost		
	Low	Base	High	Low	Base	High
EF_{cr}(gCO_2/hr.)	22,947	28,684	34,421	21.406	21.402	21.399
EF_{idl}(gCO_2/hr.)	147	184	221	18.156	21.402	21.404
EF_s(gCO_2/stop)	7,057	8,821	10,585	21.403	21.402	21.403

Table A.12. Tipping Point Demands (trip/mi/hr) that Justify Transit over Private Cars for β =$15/hr (electricity energy source is coal).

Transit Technology	Toyota Prius II (Hybrid)		Cheverolet Cavalier 2.2L	
	GC Basis	GHG Basis	GC Basis	GHG Basis
Full BRT	15.93	1.96	13.98	0.27
Tram	48.10	5.98	53.94	0.85
LRT	51.65	1.01	43.15	N/A
MHR	219.15	32.01	192.20	2.74

Table A.13. Tipping Point Demands (trip/mi/hr) that Justify Transit over Private Cars for β =$15/hr (electricity energy source is offshore wind).

Transit Technology	Toyota Prius II (Hybrid)		Cheverolet Cavalier 2.2L	
	GC Basis	GHG Basis	GC Basis	GHG Basis
Full BRT	15.93	1.96	13.98	0.27
Tram	49.35	N/A	53.94	N/A
LRT	94.13	N/A	75.01	N/A
MHR	217.02	N/A	217.02	N/A

Table A.14. Technology Energy Required Comparison

Energy Source	Emission for Electricity gCO_2e/kWh	Technology	Emission Factors		
			Stopping $gCO_2e/stop$	Cruising gCO_2e/hr	Idling gCO_2e/hr
Coal-PC	820	MHR	3152	220,956	226
		Tram/LRT	928	20,913	226
Natural Gas	490	MHR	1883	132,035	135
		Tram/LRT	555	12,497	135
Solar PV	48	MHR	184	12,934	13
		Tram/LRT	54	1224	13
Nuclear/Wind	12	MHR	46	3234	3
		Tram/LRT	14	306	3
Diesel		BRT	183	28,684	8821
		MT Bus	161	28,684	8821
		DBL Bus	150	28,684	8821

Table A.15. GHG Emissions 20% Change. Capture the Effects of GC when Coal is used as fuel consumption

Parameter	Parameter Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Tram/Light Rail Transit (LRT)						
EF_{cr}(gCO_2/hr.)	16,731	20,913	25,096	65.01/61.75	65.00/61.75	65/62
EF_s(gCO_2/stop)	743	928	1,114	65.00/61.75	65.00/61.75	65/62
EF_{idl}(gCO_2/hr.)	180.8	226	271	65.00/61.75	65.00/61.75	65/62
Metro Heavy Rail (MHR)						
EF_{cr}(gCO_2/hr.)	176,765	220,956	265,148	255.179	255.159	225
EF_s(gCO_2/stop)	3,025.6	3,782	4,438.4	364.854	255.166	225
EF_{idl}(gCO_2/hr.)	180.8	226	271	255.169	255.169	225

Table A.16. GHG Emissions 20% Change. Capture the Effects of GC when Nuclear/Offshore is used as fuel consumption

Parameter	Parameter Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Tram/Light Rail Transit (LRT)						
EF_{cr}(gCO$_2$/hr.)	245	306	367	65.0/61.7	65.0/61.7	65.0/61.7
EF_s(gCO$_2$/stop)	10.88	13.6	16.32	65.0/61.7	65.0/61.7	65.0/61.7
EF_{idl}(gCO$_2$/hr.)	2.64	3.3	3.96	65.0/61.7	65.0/61.7	65.0/61.7
Metro Heavy Rail (MHR)						
EF_{cr}(gCO$_2$/hr.)	2587	3234	3880	255.11	255.11	255.11
EF_s(gCO$_2$/stop)	36.90	46.13	55.35	255.11	255.11	255.11
EF_{idl}(gCO$_2$/hr.)	2.64	3.3	3.96	255.11	255.11	255.11

Table A.17. GHG Emissions 20% Change. Capture the Effects of GC when Solar PV-Utility is used as fuel consumption

Parameter	Parameter Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Tram/Light Rail Transit (LRT)						
EF_{cr}(gCO$_2$/hr.)	979	1,224	1,469	65.0/61.7	65.0/61.74	65.0/61.7
EF_s(gCO$_2$/stop)	43.5	54.33	65.2	65.0/61.7	65.0/61.74	65.0/61.7
EF_{idl}(gCO$_2$/hr.)	2.64	3.3	3.96	65.0/61.7	65.0/61.74	65.0/61.7
Metro Heavy Rail (MHR)						
EF_{cr}(gCO$_2$/hr.)	10,347	12,934	15,521	255.11	255.11	255.11
EF_s(gCO$_2$/stop)	148	185	221	255.11	255.11	255.11
EF_{idl}(gCO$_2$/hr.)	10.56	13.2	13.2	255.11	255.11	255.11

Table A.18. GHG Emissions 20% Change. Capture the Effects of GC when Natural Gas is used as fuel consumption

Parameter	Parameter Value			Generalized Cost		
	Low	Base	High	Low	Base	High
Tram/Light Rail Transit (LRT)						
EF_{cr}(gCO_2/hr.)	9,998	12,497	14,996	65.0/61.7	65.0/61.74	65.0/61.7
EF_s(gCO_2/stop)	444	555	666	65.0/61.7	65.0/61.74	65.0/61.7
EF_{idl}(gCO_2/hr.)	108	135	162	65.0/61.7	65.0/61.74	65.0/61.7
Metro Heavy Rail (MHR)						
EF_{cr}(gCO_2/hr.)	105,628	132,035	158,442	255.15	255.14	255.14
EF_s(gCO_2/stop)	1,507	1,883	2,260	255.14	255.14	255.14
EF_{idl}(gCO_2/hr.)	107.8	134.8	161.7	255.14	255.14	255.14

APPENDIX B

PRIVATE VEHICLES MODEL PARAMETERS TABLES

Table B.1. Private Automobile Model Parameters (typical values used for analysis)

Parameter	Symbol	Unit	All Private Vehicles
Vehicle Occupancy	c	trips/veh	4
Cycle Time Length	C	hour	0.01667
Average Trip Length	l	mile	8.1
Length of the Route	L	mile	20
Cost of Vehicle per Stopping	c_s	\$/stop	0.1
Cost of Vehicle per Distance	c_d	\$/veh-mi	1.609
Cost of Vehicle per Time	c_t	\$/veh-hr	78
Access Time	v_a	mi/hr	3.1
Commercial Speed	v_t	mi/hr	19.263
Free-Flow Speed	v_f	mi/hr	27.962
Value of Emission	γ	\$/gCO_2eq	varies

Table B.2. Light-Duty Private Vehicles Studied. Source: (Frey et al., 2002; Wu et al., 2015)

Year	Fuel Consumption	Engine Displacement	Make	Model
2007	Full Hybrid Electric	1.5L	Toyota	Prius II
2005	Gasoline	2.2L	Chevrolet	Cavalier

Table B.3. Light-Duty Private Vehicles Calculated Generalized Cost

Year	Fuel Consumption	Engine Displacement	Make	GC(\$/trip)
2007	Full Hybrid Electric	1.5L	Toyota	19.82
2005	Gasoline	2.2L	Chevrolet	21.20

Table B.4. Calculated Emission Factors for ICE (Chevy 2.2L) and HEV (Prius II) Private Vehicles using VSP Method

Operating Mode	Units	ICE Emissions	HEV Emissions
Cruising, EF_c	(gCO_2 per hr)	9864	3384
Idling, EF_i	(gCO_2 per hr)	3492	396
Stopping, EF_s	(gCO_2 per stop)	21	22

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