SUSTAINABILITY FRAMEWORK FOR URBAN TRANSPORTATION MODES AND EXPLORATORY APPLICATIONS

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAIʻI IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

CIVIL ENGINEERING

DECEMBER 2011

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ACKNOWLEDGEMENTS

Throughout my years in University of Hawaiʻi, Manoa there were many people without whom most probably I would not have been able to complete this dissertation.

First and foremost, I would like to express my gratitude to my advisor Dr. Panos D. Prevedouros for his guidance, supportive knowledge, patient guidance, time, ideas and encouragement throughout the completion of this dissertation. I would like to thank him for teaching me to enjoy what I am doing, be open to new ideas and enjoy the trip that leads to the destination of every goal of mine. I express my sincere appreciation to a big mentor for my scientific career and my personal life.

I would like to thank my dissertation defense committee members, Dr. Ricardo Archilla, Dr. Farshad Rajabipour, Dr. Michelle H. Teng and Dr. Peter G. Flachsbart. Their time and valuable suggestions resulted in valuable updates to my work. Particularly, I want to express my sincere thanks to Dr. Peter G. Flachsbart, who provided me with useful research material and papers, and supported me for attending and presenting my research in conferences. In addition, I want to thank Dr. Eftihia (Teti) Nathanail, who provided me with valuable comments and discussions on the papers prepared for journals and presented at conferences.

I want to express my appreciation to all of the undergraduate and graduate students who worked with me in the Transportation and Traffic Laboratory at the University of Hawaiʻi, Manoa since the beginning of my doctorate studies. I want to also express my gratitude to all faculty members, my lecturers and staff of the Civil and Environmental Engineering Department, and especially to Ms. Janis Kusatsu and Ms.

Amy Fujishige for helping me since my very first day in the university and for making my academic life much easier.

I would like to thank all my friends, and especially those from Greece and Cyprus for their love and support. I wish to express my gratitude and deep appreciation to older friends that faithfully supported me since the beginning of my doctorate studies and newer ones that shared with me stressful moments until the completion of my dissertation. You inspired my total effort despite the enormous work pressures I was facing. Also, I would like to thank Ms. Yvonni Siagos for always supporting me and being a true friend of my life and being there for me with a non-stop effort while remind me the important perspectives of life through endless discussions. My gratitude also goes to Dr. Andreas Mylonakis for sharing with me his experience and memories in the research arena, and making Hawai‘i be like home. On the whole I would like to thank everyone who shared a moment with me during my stay in Hawai‘i, including those that visited me.

Last but definitely not least I want to thank my family for their unconditional love, help and support through these years. My sister Persefoni Mitropoulos who assisted me several times during my studies and explained me various aspects of computer software. I want to express my gratefulness to my father Konstantinos Mitropoulos who’s been a practicing civil engineer for over three decades and my mother Dimitra Mitropoulos who has always stood by my side all these years with innumerable efforts. I dedicate this dissertation to them. Thank you.

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December 2011

ABSTRACT

Increasing environmental concerns as well as economic and social impacts of transportation in communities necessitate the incorporation of sustainability into the planning process. The common approach for sustainability assessment in transportation considers only personal vehicles or all modes present on a section of a network using aggregate measures of performance. The accelerated development and introduction of vehicles with alternative propulsion systems compel a detailed breakdown of vehicle components and characteristics for the proper understanding of their sustainability performance and impacts over their entire life cycle.

This study develops a long-term sustainability-based comprehensive framework for the life cycle assessment of any urban transportation mode. In developing a life cycle sustainability framework (LCSF), the generic structure components of a transportation system and the restrictions that may be faced in its development and implementation are considered. LCSF consists of seven fundamental dimensions that govern transportation systems: (1) Environment; (2) Technology; (3) Energy; (4) Economy, (5) Users and other stakeholders, (6) Legal framework, and (7) Local restrictions.

LCSF is used to assess the sustainability performance of 11 vehicles with a variety of propulsion technology. The vehicles are ranked based on their performance per sustainability dimension, and overall sustainability. Gasoline pickup truck (GTP) and gasoline SUV are the most energy demanding vehicles. Hybrid electric are the least energy demanding vehicle per vehicle mile traveled over its life cycle, with 44% lower energy requirements than an internal combustion engine vehicle. Car Share and BRT have the lower energy consumption per passenger mile traveled (PMT).

Vehicle-specific results were combined in a tool to perform a sustainability assessment of Atlanta, Chicago and OPTIMUS – a hypothetical metropolitan area with superior transportation sustainability elements. Normalized indicators per metropolitan area are aggregated into a sustainability dimension index (SDI) and an overall sustainability index (OSI). Both SDI and OSI are used to reveal dimension specific and overall sustainability tradeoffs for each alternative when different characteristics, policies, scenarios and assumptions are used. The sustainability LCSF with its proposed indicators provides a workable method both for sustainability assessment in transportation planning and for facilitating policy analysis and decision-making.

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LIST OF ABBREVIATIONS

BRT	Bus Rapid Transit
CH_4	Methane
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CS	Car Share
DB	Diesel Bus
DPF	Diesel Particulate Filter
EIO-LCA	Economic Input Output Life Cycle Assessment
EV	Electric Vehicle
EU	European Union
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
GPT	Gasoline Pickup Truck
GSUV	Gasoline Sports Utility Vehicle
GWP	Global Warming Potential
NO_x	Nitrogen Oxides
N_2O	Nitrous Dioxide
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
LCSF	Life Cycle Sustainability Framework

LCST	Life Cycle Sustainability Tool
LCI	Life Cycle Inventory
MCDM	Multi Criteria Decision Making
OSI	Overall Sustainability Index
PHEV	Plug-In Hybrid Electric Vehicle
PM_{10}	Particulate Matter 10 micrometers in diameter or smaller
PMT	Passenger Miles Traveled
SDI	Sustainability Dimension Index
SEA	Strategic Environmental Assesment
SO_x	Sulphur Oxides
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
WTW	Well to Wheel

CHAPTER 1

INTRODUCTION

1.1 Background

Sustainability is a term of high interest and has been used widely, especially within the last few years to describe the maintenance of a balance within the system. Initially, it was used to depict concerns mostly associated with environmental issues, and grew to include energy, economy and social issues.

Different points of view, desired objectives and goals pursued by every community (e.g., region, nation, group of states or nations) require adjustments in sustainability definitions and approaches. There are various sustainability definitions addressing the needs of different communities. The most frequently quoted definition was provided by the World Commission on Environment and Development (WCED 1987) and defined sustainable development as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The three pillars that underpin sustainability, namely the environment, the society and the economy, are the ones most widely used in sustainability.

The substantial impacts of transportation on environment, society and economy strongly urge the integration and incorporation of sustainability into transportation. Defining sustainable transportation is the first step towards setting goals and objectives, and delivering analytical procedures to account for sustainability goals. A comprehensive definition of sustainable transportation that includes most of the social, economic and environmental concerns is provided by the European Council of Ministers of Transport

(ECMT 2001, pp.16.) It defines a sustainable transportation system as one that 1) allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations, 2) is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy, 3) limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.

While there is no standard definition for sustainable transportation to be used for implementing sustainability in a system, the immense impacts of the transportation sector on the environment and economy, and the social effects on communities necessitate the incorporation of sustainability into the transportation planning process.

A few sustainability frameworks have been developed for understanding transportation in the context of sustainability and for creating metrics such as criteria and indicators. These metrics are used to assess sustainability of different transportation systems and monitor progress towards it. There is no universally accepted framework for assessing sustainability. Research has been conducted mostly after 2000 by universities and institutes on sustainability performance measures that have the potential to move a transportation system towards sustainability. The Center for Sustainable Transportation (CTS 2002) developed and used indicators to study whether the transportation sector improves in respect to its adverse impacts on environment and health. Sustainability indicators are usually developed to assess the impact of transportation on the three principal sustainability dimensions (i.e., environment, economy and society) whereas other studies provide measures for a fourth sustainability dimension, system effectiveness.

This study identifies the complex and abstract definitions of sustainability and recognizes that the introduction of a framework that can embrace regional, national or global goals at a disaggregate level and translate these goals into comprehensive assessments for informed decision making is essential.

1.2 Problem Statement

Planning methods chiefly assess the impact of transportation systems on the environment, e.g., Environmental Assessments, Environmental Impact Statements and other reports required by NEPA for the introduction or expansion of transportation systems. Transportation needs are balanced with environmental, social and economic factors, such as in the FHWA NEPA process. Moreover, transportation is coordinated with other sectors including housing, environmental policies and investments to strengthen the importance of environmental, social and economic sustainability, e.g., The Partnership for Sustainable Communities composed by the EPA, U.S. Department of Transportation (DOT) and U.S. Department of Housing and Urban Development.

The substantial impacts of transportation on environment, society and economy strongly urge the incorporation of sustainability into transportation planning. Several governmental and regional agencies have applied sustainability to their transportation programs. Jeon and Amekudzi (2008) studied the sustainability initiatives in North America, Europe and Oceania and reported that a standard definition of transportation system sustainability which is followed by a standard set of indicators for the assessment of transportation systems is not available. However, the majority of these studies share common transportation system objectives such as the mobility of people and goods, accessibility and safety, and preservation of environmental resources.

A traditional transportation mode evaluation is based on demand and supply comparisons, cost and benefit evaluations, financial risks analysis, and cost-effectiveness analysis. Recent assessments begin to focus on detailed energy requirements and pollution emissions during the operational stage whereas other applications attempt to internalize the cost of accidents and travel delays. In short, there are multiple view points for assessing modes of transportation due to their important and pervasive impacts to society and economy, both positive and negative. However, a framework that has the potential to assess the long term sustainability of any transportation mode throughout its life cycle is not available. This research effort attempts to close this void in the state of the art starting with a framework that has its foundations in the over-arching principle of sustainability.

Attempts at incorporating sustainability into transportation planning have resulted in research on the development of variables defined as measures, indicators or indices representing elements of sustainability. Transportation sustainability indicators that measure impacts on mobility, safety and environmental effects are applied mainly to the operational stage of the transportation system. However, major components of sustainable transportation are omitted in this approach, including infrastructure construction, vehicle manufacture, maintenance and disposal. Furthermore, past studies that assessed transportation sustainability, consider only personal vehicles or all modes present on a section of a network by using aggregated measures such as average speed (to measure the ability to overcome long distances in shorter time, which is a dimension of mobility), total vehicle emissions (to measure air pollution or green house gas impact) and total fatalities or injuries (to measure safety) to evaluate sustainability performance. The aggregation of transportation performance measures limits one of the sustainability's roles in transportation planning, which is to assist agencies in evaluating new transportation modes that are proposed for introduction in a network and forming policies for a viable transportation performance in the long term.

The accelerated development and introduction of vehicles with alternative propulsion systems compel a detailed breakdown of vehicle components and characteristics for the proper understanding of their performance and impacts over their entire life cycle. Disaggregation per vehicle type in a transportation network and life cycle sustainability assessment for each type may lead to more accurate planning and policy making. Sustainability assessment per vehicle type will reveal the critical characteristics for considered vehicles and determine the tradeoffs for different indicators. Sustainability assessment should be combined with specific policies per vehicle type and reveal the parameters that improve sustainability marginally or universally. Thereafter, policies can be formed and modified to support decision making in transportation planning.

1.3 Research Objectives

The goal of this dissertation is to develop a generalized life cycle sustainability framework for the assessment of transportation alternatives, and customize the framework for application in urban transportation by developing specific objectives and indicators that represent mode characteristics and needs. The objectives of the proposed research are:

- Identify the sustainability dimensions that structure and manage the development and implementation of a sustainable transportation system.
- Determine adequate performance measures that cover the spectrum of sustainable transportation, represent critical vehicle characteristics that affect sustainability performance and enable the comparison of transportation modes over their life cycle.
- Propose a complete methodology for assessing the sustainability of any transportation mode over its life cycle by using the proposed sustainability dimensions and mode characteristics.
- Develop a life cycle sustainability tool for incorporating sustainability in transportation planning by using disaggregated results per vehicle to determine overall sustainability performance of a transportation network.

1.4 Research Contribution

This dissertation presents the most comprehensive sustainability assessment for urban transportation modes published to date by considering life cycle impacts. The outcome of this research is a life cycle sustainability tool that can be expanded, modified and utilized to provide a sustainability assessment at a global or regional level.

The contribution of this research towards the incorporation of sustainability into transportation planning is threefold. First, it develops a comprehensive sustainability framework with a set of indicators for the life cycle sustainability assessment of transportation modes vis-à-vis sustainability assessment based solely on the operation stage of modes. The indicators used herein are organized into sustainability dimensions (Environment, Technology, Energy, Economy, Users, Legal Framework and Local

Restrictions) that do not cross sustainability dimension boundaries as it occurs by using the traditional triple bottom line approach (Environment, Society, Economy.) Second, it disaggregates transportation modes based on their characteristics (i.e., technological, operational and functional characteristics) and assesses transportation sustainability according to the vehicle population with similar characteristics present on a network or on a section of it. Third, it develops a life cycle sustainability tool, which is composed by a set of sustainability indices and a visual interface, to present the "best" alternative and the tradeoffs among assessed transportation modes, and to support the decision-making process in transportation planning.

This research updates the state of the art in three main areas: (1) it takes a well-to-wheel approach of modes instead of focusing only on the operation of modes, (2) it disaggregates modes instead of focusing on personal vehicles, and (3) it explicitly assesses most current fuels and propulsion technologies instead of focusing on fossil fuel powered modes.

1.5 Dissertation Structure

This dissertation is structured in seven chapters. This introductory chapter is followed by Chapter 2 which summarizes the literature review on definitions for sustainability, sustainable development and sustainable transportation along with research on sustainability models, frameworks and performance measures. The last part of Chapter 2 reviews decision making models for multi criteria decision making. Chapter 3 focuses on the literature of life cycle assessment methods and presents life cycle assessment applications in transportation sector and the limited literature available on the implementation of life cycle assessment in sustainability and sustainable transportation. Chapter 4 discusses the research methodology, presents the developed life cycle sustainability framework with its dimensions, objectives and indicators, and reviews the vehicle technologies and tools that are used in the sustainability assessment. Chapter 5 presents the data sources and the assumptions for the modeling of vehicles. The defined sustainability indicators are quantified and presented for each vehicle type and dimension, and they are normalized to provide a comparison of sustainability performance per sustainability dimension and overall sustainability. Chapter 6 presents a case study that explores the application of the life cycle sustainability framework in three metropolitan areas with different transportation and demographic characteristics. Chapter 7 summarizes the research process of this dissertation and provides conclusions, and recommendations for future work based on the limitations of this work and on potential life cycle sustainability assessment applications in transportation.

CHAPTER 2

SUSTAINABILITY AND SUSTAINABLE TRANSPORTATION

2.1. Introduction

This chapter is the first part of the literature review. It addresses the concept of sustainability and its implementation into transportation planning for the assessment of existing or new projects. It examines the state-of-the-knowledge as of mid-2011 and presents existing work on sustainability and sustainable transportation. The chapter is divided into five major parts. First, sustainability definitions, the differences between sustainability and sustainable development and the models that are used to depict the relationship between sustainability dimensions are reviewed. Transportation impacts that led to the accelerated incorporation of sustainability into transportation planning are outlined, and sustainable transportation definitions are summarized in section 2.3. In the third part, sustainability framework types and performance measures that are used in sustainability assessment projects are explored. In the fourth part a number of studies that have implemented sustainability frameworks and indicators in sustainable transportation assessment are identified. In the last part multiple criteria decision making methodologies and their application in transportation and energy studies are reviewed.

2.2. Sustainability and Sustainable Development

In this part of the literature review, definitions, differences between sustainability and sustainable development terms and sustainability's growth to embrace environment, society and economy as its basic dimensions are presented. Then, the most used models that have been developed by different disciplines (e.g., development, transportation) to depict the relationship between sustainability dimensions and the goals that led to those models are reviewed.

2.2.1. Defining Sustainability

Sustainability is a term of high interest which has been used widely in the last few years to describe materials, products and processes as well as behaviors, systems and communities. Different points of view and desired goals and objectives pursued by each community (e.g., subdivision, suburb, metro area, region, nation, group of nations) or stakeholder (e.g., agency, institute, organization, private or public company) require adjustments in sustainability definitions and approaches. There are literally dozens of sustainability and sustainable development definitions; Pearce and Walrath (2005) have compiled two hundred sustainability definitions from literature.

Although a consensus has not been developed yet on a unique sustainability definition, there was a necessity expressed by stakeholders and communities to relate present living needs, environmental capacity and economic growth with future generations. Past abstract working frameworks, which were making the development of environmental policies a problematic procedure, combined with the need to balance objectives and maintain success in the long term, led to sustainability and sustainable development definitions.

Let’s understand the difference between the two terms: Sustainability is the capacity of a system to continue in time. Tietenberg (1984, pp.94) claims that “The sustainability criterion suggests that, at a minimum, future generations should be left no worse off than current generations.” This definition implies the present generation should maintain and pass to the next generation the same if not more resources to satisfy their living needs. The National Commission on the Environment (1993, pp.2) defines sustainability as “a strategy for improving the quality of life while preserving the environmental potential for the future, of living off interest rather than consuming natural capital.” Sustainable development directly relates to the growth of human population inherently involving economics (O'Grady 2007.) These two terms are the subject of section 2.2.2 and 2.2.3.

2.2.2. Sustainability Concepts

Three pillars underpin sustainability: the environment, the society and the economy. Although they embrace a vast number of parameters that often cross borders, they are still the most widely used in sustainability. Sustainability achievement of an outcome is based on performance measures that express environmental, social and economic concerns.

The need to depict the dimensions or the fundamental components of sustainability and their interactions led to the development of several conceptual models. The goals and objectives set by each community or organization lead to concepts that share similarities and differences. The majority of these concepts use the environment, the society and the economy as their fundamental dimensions.

The most commonly used concepts are the Venn diagram or triple bottom line model, and the strong sustainability model; both shown in Figure 2.1 (International Union for Conservation of Nature 2006.) In both models, environment, society and economy are the main dimensions that are used to assess a system’s sustainability performance.

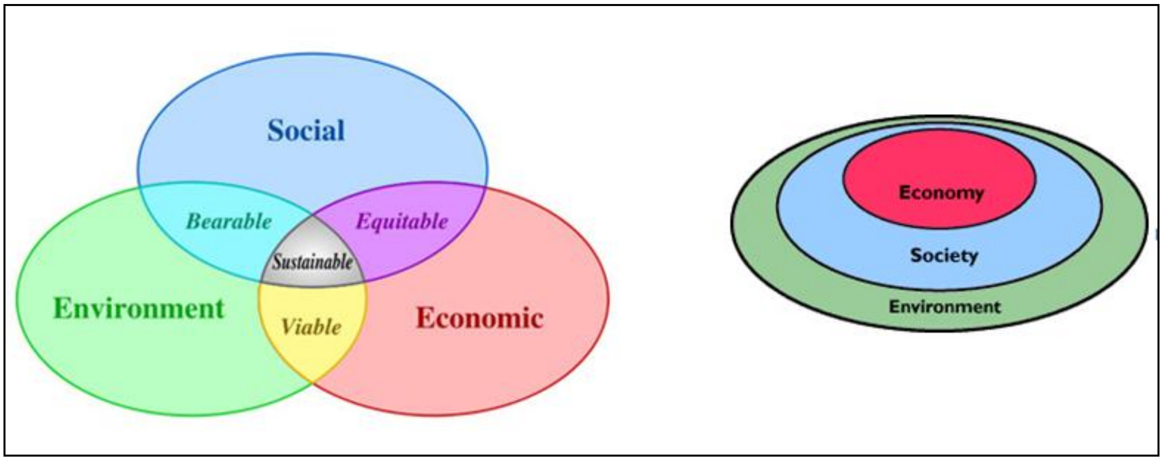

Figure 2.1. Weak and Strong Sustainability Models

The triple bottom line model asserts that what is required is balance between economic, environmental and social outcomes. Usually this model is referred to as the "weak sustainability model" as there are no limits on economic and social activities imposed by the environment and these activities may not occur within the carrying capacities of environment (biosphere.) The prevailing activities related to economy dominate the social and environmental activities. Their intersection represents the possibility of sustainability (SANZ 2009.)

On the contrary, the strong sustainability model shows that there are restrictions, imposed by the environment, on social and economic related activities. To illustrate this argument, the strong sustainability model uses ellipses and places the three sustainability dimensions in order of significance. The diagram represents the fact that the earth-environment is a system, that all human-social actions occur in it, and that not all the social activities are related to economy. In comparison with the weak sustainability model, the strong model illustrates that economy is dependent on society, while in the weak one society depends on the economy. Both models have been adopted by different communities to promote their sustainability plans (SANZ 2009.)

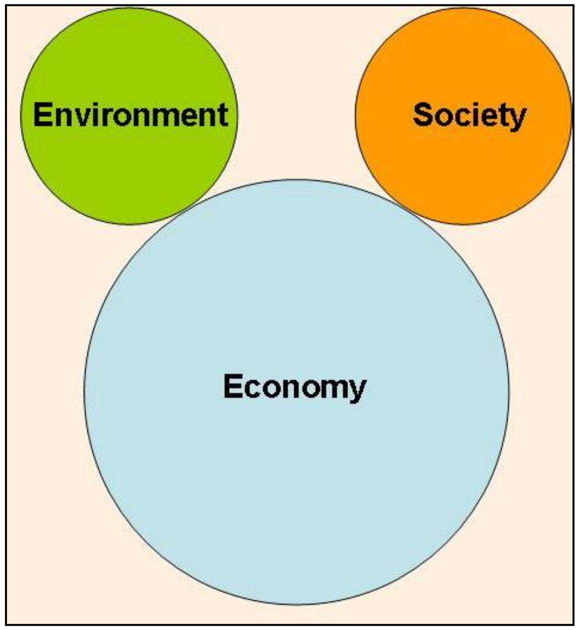

Figure 2.2. Mickey Mouse Model of Sustainability

Another sustainability diagram which is usually been adopted by most companies to promote their economic growth and that underpins economic decision making in business is the Mickey Mouse model (Figure 2.2.) Based on this model the economy is set as the foundation of the system, and consequently fails to conserve the environmental resources, because all processes aim to grow economy unsustainably, and therefore environment is ravaged.

2.2.3. Sustainable Development

The most frequently quoted and well known definition for sustainable development was given by The World Commission on Environment and Development (WCED 1987.) It defined sustainable development as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- The concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given, and
- The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

This definition may be characterized as anthropocentric as it omits to address the other living species that share the same space with human beings. In addition to this point, it leaves out environmental limits and equity. McCormick (1991, pp.150) states that a more appropriate and universal definition would define sustainable development as "development that occurs within the carrying capacity of the natural and human environment." In an attempt to address all the major parameters of development, sustainability definitions grew to include economy and society. Pearce and Warford (1993, pp.8) gave emphasis on the environmental quality towards the objective of raising real income by stating that "sustainable development describes a process in which the natural resource base is not allowed to deteriorate. It emphasizes the hitherto unappreciated role of environmental quality and environmental inputs in the process of raising real income and the quality of life."

The Group of Seven (1989, pp.A5) contributed key ideas to the sustainability definition, which are connected to the environmental performance of communities and affect economic growth. Their definition quotes that "Environmental protection is integral to issues such as trade, development, energy, transport, agriculture and economic planning. Therefore environmental considerations must be taken into account in economic decision-making. …In order to achieve sustainable development, we shall ensure the compatibility of economic growth and development with the protection of the environment. Environmental protection and related investment should contribute to economic growth."

The World Health Organization (WHO 2005, pp.8) committed to undertake actions and measures at all levels to achieve sustainable development and focused on the triple bottom line approach – environment, society and economy – rather than on the environmental part of it. "These efforts will also promote the integration of the three components of sustainable development –economic development, social development and environmental protection – as interdependent and mutually reinforcing pillars. Poverty eradication, changing unsustainable patterns of production and consumption and protecting and managing the natural resource base of economic and social development are the overarching objectives of essential requirements for sustainable development."

From these definitions, it can be seen that there is a tendency to use three fundamental dimensions of life as the core of sustainability: Environmental protection, Economic welfare and Social well being.

- Environmental Sustainability engages the maintenance of natural resources, avoids depletion of non-renewable resources when these are not replenished in adequate natural rates, and it ensures that present processes take place within environmental limits that preserve the capacity of the natural environment. Environmental degradation means inability of its habitats and species to sustain life.

- Social Sustainability seeks to achieve a healthy, safe, fair, accessible and equal environment for all habitats within which people participate, interact and receive social services such as education, employment, recreation and cultural development.
- Economic Sustainability ensures the production and delivery of goods and services on a continuing basis, to present and future generations. It maintains the necessary wealth to provide a high quality of life and it avoids economical imbalances which damage the economy.

2.3. Transportation and Sustainability

Sustainability interest in development and transportation has grown mostly the last decade due to the environmental, social and economic impacts that these activities have on communities. Rapid technological development and increasing mobility needs for people and goods leveraged the number of motor vehicles globally. The outcomes of this growth imposed severe impacts on the carrying capacity of the environment, while communities tried to preserve social and economic welfare. The following sections outline these issues and provide the most dominant definitions for sustainable transportation.

2.3.1. Motor Vehicle Growth and Transportation Impacts

Continuous growth of road transportation contributes in the consumption of significant quantities of energy and materials and in the deterioration of air quality and climate conditions around the world. Transportation activities in U.S. accounted for 33%

of CO_2 emissions from fossil fuel combustion in 2009, and nearly 65% of the emissions resulted from gasoline consumption for personal vehicle use (EPA 2011a.)

Passenger cars in the U.S. were accounting for 55% of the total 247 million cars and trucks being in use in 2008 (Davis et al. 2010.) Since the late 1990s, light trucks (i.e., trucks up to 8,500 pounds, including most midsize and large SUVs) have replaced passenger cars and the effects of the additional CO_2 emissions rate they generate, compared with conventional passenger vehicles, have been exacerbated. The CO_2 emissions rate of light trucks was roughly 18% higher than that of passenger cars in the early 1970s. Recently, CO_2 emissions from light trucks estimated to be 40% higher than those of passenger cars. Figure 2.3, shows the contribution of different vehicle types in carbon emissions (DeCicco et al. 2005.) By 1998 sport utility vehicles (SUVs) became the vehicle class with the highest carbon burden and they have maintained this status.

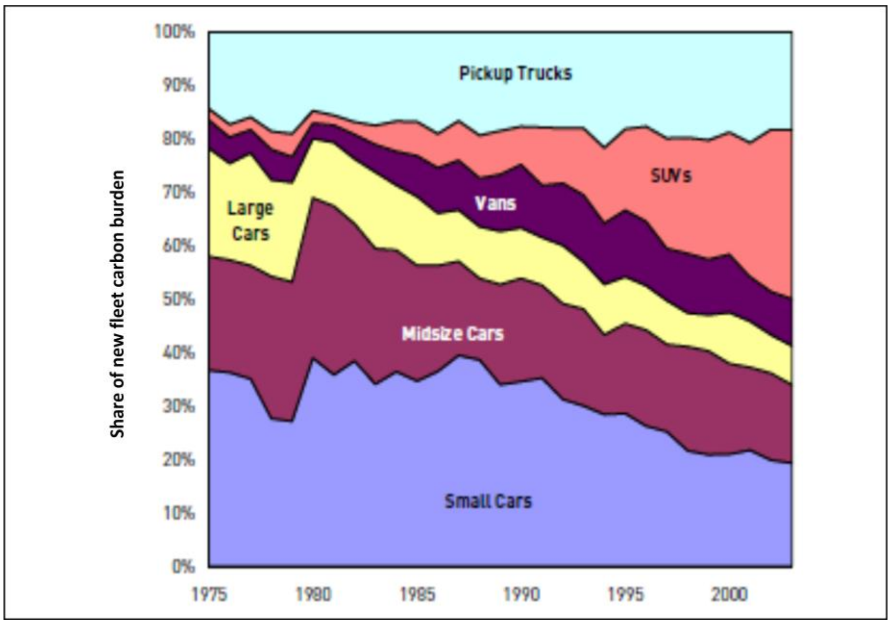

Figure 2.3. New Fleet Carbon Burden Share by Major Vehicle Class, 1975-2003

Figure 2.4 illustrates how various factors, such as the growth in vehicle miles of travel and changes in fuel efficiency, have affected automotive carbon emissions (Davis et al. 2003.) Petroleum accounted for 93.8% of all transportation energy sources in 2009. The high consumption of petroleum, which is a non-renewable source of fuel, combined with the high percentage of car utilization in the U.S. to maintain personal mobility reveal the significant role that road transportation plays in environmental issues of communities (Davis et al. 2010.)

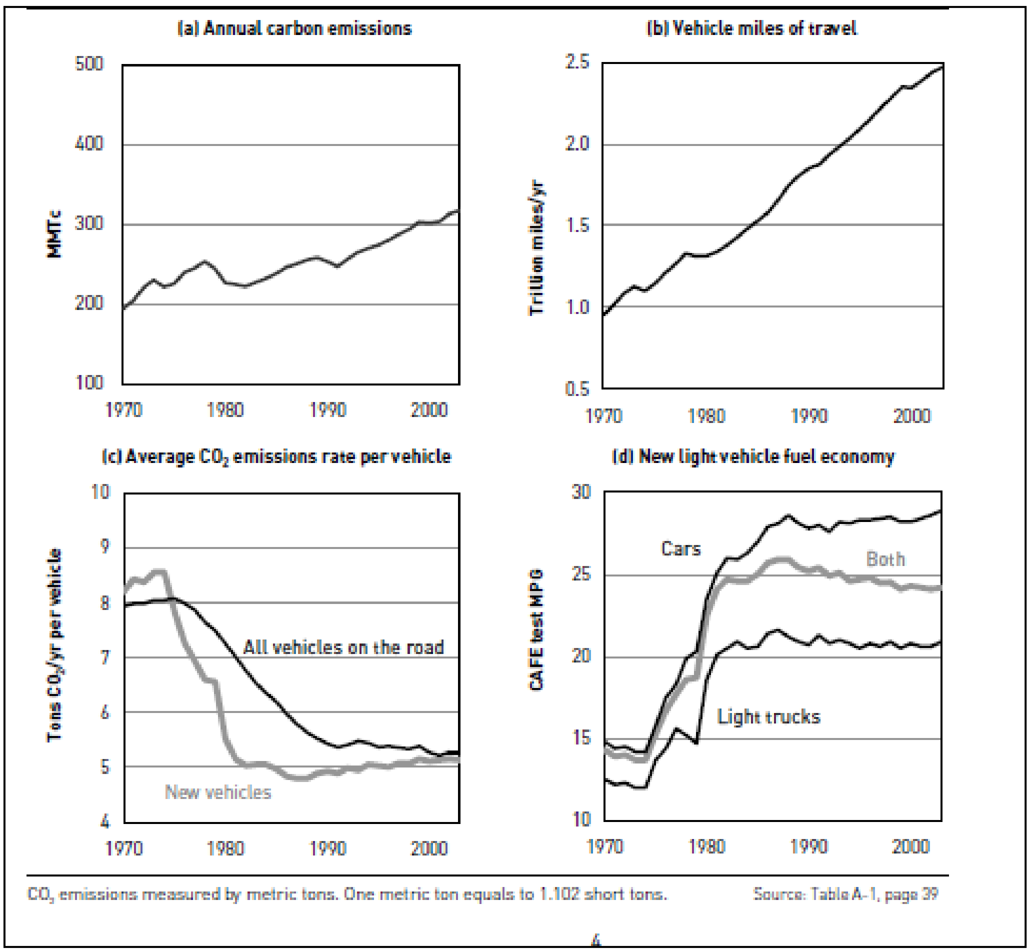

Figure 2.4. Historical Overview of U.S. Light Vehicle Carbon Emissions

As mobility and the number of vehicle increases, transportation impacts increase too. In large metropolitan areas travel has increased by 105% between 1987 and 2007, resulting in traffic congestion, which is a beacon for an unsustainable transportation system and causes a multitude of environmental, social and economic problems (Shrank et al. 2008.) Many urban freeways across the U.S. operate at saturated levels for several hours every day. Urban congestion relief is a priority in the national transportation agenda due to the significant impacts it imposes to environment, economy and society.

The impact of transportation on the environment is multidimensional; it consumes energy, generates noise, pollutes the air, land and water, and consumes materials and land. It consumes non-renewable energy sources like oil for manufacture, operations and maintenance, consumes large amounts of materials for infrastructure construction and vehicle manufacture. Some of these processes are very energy intensive (e.g., production of cement.)

Transportation supports the economy and for the economy to grow, fast, safe and reliable movement of people and goods is required. Departments of transportation maintain, rehabilitate and manage existing infrastructure to address increasing traffic demand and design new transportation networks to increase mobility and offer accessibility to all communities.

Transportation also promotes mobility for people and goods; thus it has a role in society. Not all social activities are related to economy, but several important activities are related to transportation, such as health, education, work, recreation, meeting friends and family. Major transportation impacts on environment, society and economy include the following:

- **Non-renewable resource consumption –** The transportation sector consumed 52% of the world's liquid (crude oil and lease condensates, natural gas plant liquids, and refinery gain) energy in 2005 and its consumption is projected to increase, more rapidly than other sectors, consuming 57.9% of the world's liquid energy by 2030 (EIA, 2008.) The petroleum share of transportation energy consumption in the U.S. for 2010 was 93%. The transportation share of total U.S energy consumption was 27% and of that share 61% was used by cars and light trucks (Davis et al. 2011.) Current vehicle technologies are mainly petroleum based but those resources are not replenished at higher rates than they are consumed, therefore have a strong negative impact. Dependence solely on oil products to cover a community's transportation needs tends to undermine economic stability due to fluctuation in oil supply and pricing from market or political forces and depletes resources for future generations.
- **Emissions –** Transportation emissions are a large source of greenhouse gases (GHG). Transportation is the most rapidly increasing GHG source: From 1990 to 2003 CO_2 emissions increased by 20% in U.S. (BTS 2005.)
- **Noise –** Transportation noise is a significant environmental consideration for freeways, especially when these are designed to pass through urban communities. Increased level of noise may cause housing relocation, other land use shifts and property value reduction along the corridor. Highway transportation accounts for 60% of the total transportation noise emissions (Rodrigue et al. 2006.)
- **Traffic congestion –** The economic, social and environmental impacts due to traffic congestion on freeways are significant. Within 20 years (1985-2005) the total cost of

congestion in 85 urban areas in the U.S. increased by 85% and the total delay increased by 72% (TTI 2007.)

- **Road safety –** It is associated with environment, society and economy. Economic growth, in developed and developing countries requires increased mobility. Globally it is estimated that 1.2 million deaths and 500 million injuries occur annually due to road accidents and the number of fatalities is predicted to grow to more than two million by 2020 (WHO, 2004.)

Transportation outcomes and their impact on all three sustainability dimensions make necessary the incorporation of sustainability into transportation planning. Defining sustainable transportation is the first step towards setting goals and objectives, and delivering analytical procedures to account for sustainability attributes and goals.

2.3.2. Definitions of Sustainable Transportation

Sustainability integration and incorporation into transportation planning and engineering by governmental or private agencies implies consideration of the three sustainability dimensions presented in section 2.1.

The WCED (1987) provides the following definition, "Sustainable transportation is about meeting or helping meet the mobility needs of the present without compromising the ability of the future generations to meet their needs".

A definition of sustainable transportation that includes most of the environmental, social and economic concerns is provided by the European Council of Ministers of Transport (ECMT 2001.) It defines a sustainable transportation system as one that:

- “Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.”

The Organization for Economic Cooperation and Development (OECD 2002a, pp.16) provides a definition of a <u>sustainable transportation system</u> as a system that throughout its full life-cycle operation:

- Allows generally accepted objectives for health and environmental quality to be met, e.g., those concerning air pollutant and noise goals proposed by WHO.
- Is consistent with ecosystem integrity, for example, it does not contribute to exceedances of critical loads and levels, e.g., as defined by WHO for acidification, eutrophication and ground-level ozone.
- Does not result in worsening of adverse global phenomena such as climate change and stratospheric ozone depletion.

Several governmental and regional agencies have applied sustainability to their transportation programs. Jeon and Amekudzi (2008) studied sustainability initiatives in North America, Europe and Oceania and reported that there is not a standard definition of transportation system sustainability. However, the majority of these studies share common transportation system objectives such as the mobility of people and goods, accessibility and safety within environmental limits.

Stakeholders balance the environmental, economic and social impact of a transportation system to make it sustainable. They assess transportation system impacts on the environment, economy and society in order to characterize its “degree of sustainability.” If they do not fulfill these requirements then the system is characterized as unsustainable and stakeholders try to alter its inputs and outcomes to bring it to desirable levels.

Sustainable transportation definitions assist in the development of standardized frameworks that can be used to create and organize a set of indicators. These indicators can be used to measure how a transportation system contributes to a community’s progress towards sustainability.

2.4. Transportation Sustainability Frameworks and Performance Measures

Sustainability frameworks and performance measures have been developed for different fields of industry including chemistry, agriculture, development, water infrastructure (Rijsberman et al. 2000), built infrastructure (Pearce 2002) and mining (Azapagic et al. 2000.) While practices and processes towards the development of indicators to assess sustainability vary widely, it is a common sense that proposed indicators and criteria shall drive policy making as well as provide feedback to all users of a system.

2.4.1. Sustainability Frameworks

"The problem when assessing sustainability is not a lack of data or knowledge, but the difficulty of selecting the relevant information and condensing it in such a way that general and meaningful conclusions can be drawn." (German Federal Environment Agency 1997, pp.223.)

Data collection for the assessment of transportation systems is an intricate task. Available data determines the parameters that are going to be used in the assessment. The sustainability of a transportation system becomes possible to be assessed when the parameters that compose it can be defined and measured. These parameters should clearly show how a system can be more sustainable and what conditions should be met to be more sustainable. An integrated presentation of this process can be given in a form of a framework. A framework is developed for understanding transportation in the context of sustainability and for creating metrics such as criteria and indicators. These metrics are used to assess sustainability of different transportation systems and monitor progress towards it.

There is no universally accepted framework for assessing sustainability. Existing frameworks lack flexibility for being adopted by different communities in sustainability assessments. Classification of frameworks can be done based on the attributes of a system for which they have been developed, such as problem definition, purpose, application discipline, methodology, data collection and analysis. The most commonly used indicator based frameworks are: a) linkage based, b) impact based, and c) goal or objective based. A dynamic sustainability framework that is implemented in different systems should be adjustable to the needs and different attributes of each system.

Linkage based frameworks capture the cause-effect relationship between framework components, indicators, effective actions and impacts. An example of a linkage based framework is the Pressure-State-Response (PSR) framework.

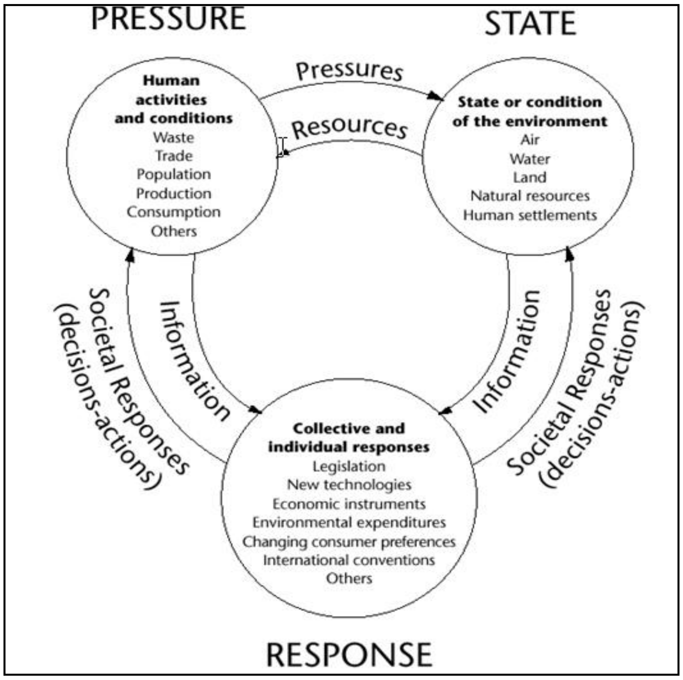

Figure 2.5. Pressure State Response Model

The PSR framework, as shown in Figure 2.5 (OECD 1999) was developed in the 1970s by A. Friend and was adopted by OECD, to provide a mechanism for monitoring the status of the environment and monitor the processes involved in environmental degradation. The PSR framework is based on the concept of causality. It states that human activities exert pressure (such as pollution emissions or land use changes) on the environment that can bring changes in the state of the quality and quantity of the environment (such as changes in ambient pollutant levels, habitat diversity, water flows.) Society responds to changes, by developing environmental and economic policies or programs to prevent, reduce or mitigate the pressures and/or the environmental and socio-economic damage that occurred or is expected to occur as a result of the original pressures (OECD 1999.) This type of framework enhances policy understanding for policy makers and stakeholders. Based on its wide usage, the PSR framework can be identified as a commonly agreed upon framework by many organizations and agencies for environmental reporting (Waheed et al. 2009.)

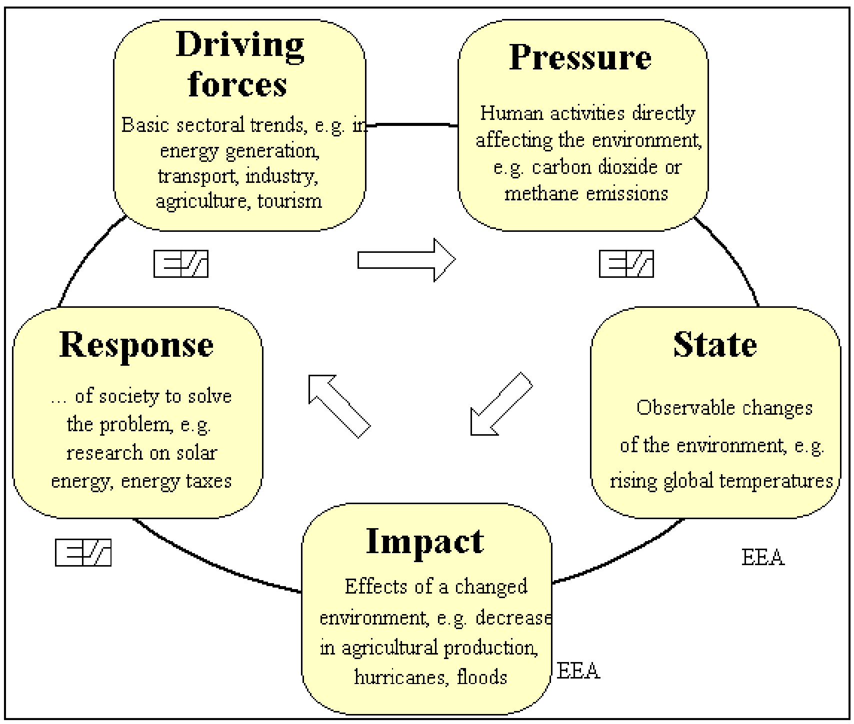

Figure 2.6. The Driving Force Pressure State Impact Response (DPSIR) Model

In addition to PSR, other common linkage based frameworks are the Driving Force Pressure State Impact Response (DPSIR) and the Driving Force Pressure State Exposure Effect Action (DPSEEA.) The DPSIR model in Figure 2.6 (E.U. 1999) is an extension of the PSR model. It expands the framework to deal more specifically with the needs for describing sustainable development. Inclusion of driving forces and impacts has broadened the scope of the model, – but the core principles remain the same. The United Nations (UN) Commission for Sustainable Development (UNCSD) bases its indicator set on the Driving force-State-Response model (DSR) model, which allows for a better inclusion of non-environmental variables (E.U. 1999.)

Many international organizations including the UN, OECD, the European Environment Agency (EEA) and the European Commission (EC), use the DPSIR framework to develop indicators (E.C. 2004, Gilbert and Tanguay 2000.)

The Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA) framework, as shown in Figure 2.7 (WHO 1997), which is based on the PSR, represents the components in a linear fashion in order to replicate the connections between factors affecting health and the environment more clearly. Pressures may be exerted on the environment, which cause development sectors to generate various types of outputs (for example in the form of pollutant emissions), causing the “state” (quality) of the environment to be degraded. The DPSEEA framework is useful as it covers the full spectrum of cause and effect relationships (WHO 1997.)

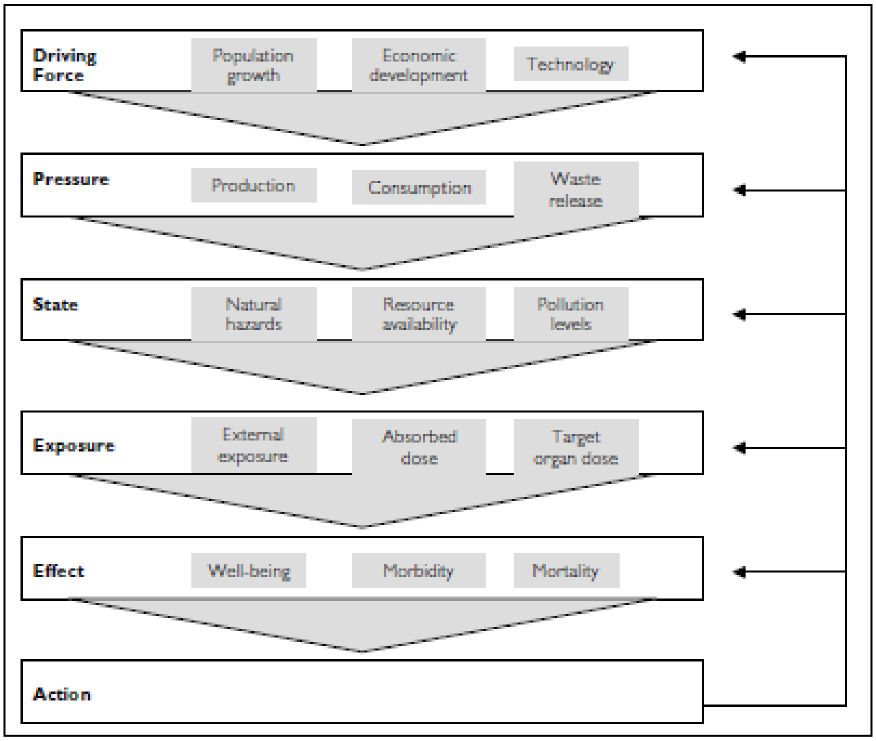

Figure 2.7. The Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA) Framework

The UN's Development Program (UNDP) recommends the adoption of the PSR framework to connect the different aspects of environmental sustainability and to monitor progress towards it. Kazakhstan's Government used the PSR model on reaching Millennium Development G7 or MDG7 (UNDP 2005.) Its Millennium Development Goal Reports focus on the state of water resources, in terms of both quantity and quality. Pressures on these resources, such as irrational irrigation practices and improper regulation of river water flows, were identified. Using the PSR model makes it possible to see how different types of indicators for environmental sustainability are connected, and to select appropriate sets of indicators to assess the progress of a country. Indicators of environmental pressures, driving forces and responses, have been used for country reporting on MDG7 (UNDP 2005.)

An additional selection of indicators of environmental pressures can be drawn from other sources of environmental indicators and indicator sets. Such as the UN's Commission on Sustainable Development (UNCSD) Theme Indicator Framework (2001), OECD's Core Set of Environmental Indicators (2002b) and Canada's Environmental Indicators Series (2003.) Indicators are derived from sectoral information (e.g., transportation, agriculture, household consumption, and tourism) as well as the natural resource accounting systems that have been established in a few countries. Indicators found in each of these sets, include forests, biodiversity, energy, atmosphere and climate change, water, sanitation and waste, agriculture and land use, and transportation.

The impact-based framework focuses on the impacts of various actions on sustainability. A common application of the impact-based framework is the three dimensional or triple-bottom line (TBL) framework of indicators based on environment, economic, and social impacts. Environmental Impact Assessment (EIA) driven integrated assessment reflects the 'three-pillar' or TBL model. Pope et al. (2004) stated that the impact-based approach to sustainability assessment attempts to ensure that impacts are not unacceptably negative overall, meaning that the acceptability criterion for a proposal is that it does not lead to a less sustainable outcome. This approach can be thought of as 'direction to target', where the exact position of a sustainable state for that particular proposal is unknown. The EIA approach to sustainability assessment is shown in Figure 2.8 (Pope et al. 2004.)

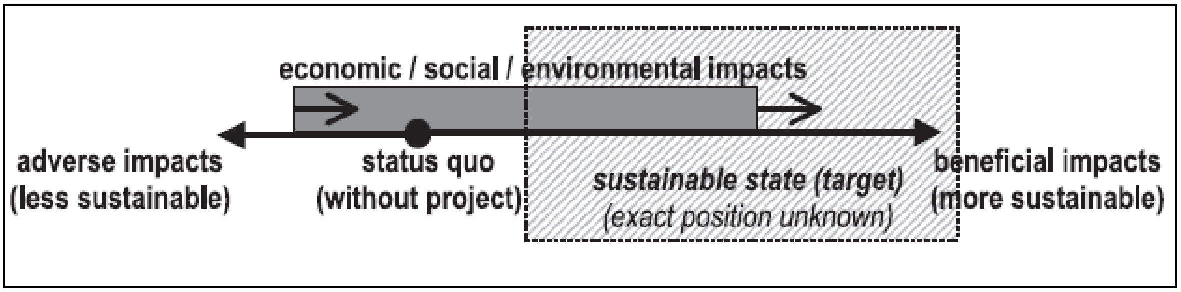

Figure 2.8. EIA Integrated Assessment Approach to Sustainability Assessment

Development of sustainability initiatives is easier since criteria or indicators are grouped under the TBL framework; however positive outcomes for one sustainability dimension (e.g., environment) might generate negative outcomes for the other two (i.e., society and economy.) To be truly integrated, the interrelations between the three 'pillars' of impacts must be considered (George 2001.)

Pearce and Vanegas (2002) used the impact-based framework and the concept of systems to develop a sustainability framework for built environment systems by: a) differentiating among the possible scales (global and technological systems) on which sustainability is a relevant concept, b) identifying key thresholds that represent sustainability constraints, and c) using these parameters as dimensions to represent sustainability and to construct a decision space for assessing performance of different facility systems. The three objectives, occurring from physical constraints, are: a) motivation of initiators, b) intergenerational equity (between generations), and c) intragenerational (within generations) equity. Based on these objectives, the three parameters which are used to define sustainability are: 1) human species, 2) resources (consumption), and 3) ecosystems.

Three more objectives are defined for technological systems, as follows: a) minimizing negative impacts to resource bases, b) satisfying human needs and aspirations both now and in the future, and c) causing minimal negative ecological impacts. At the technological level the parameters are: 1) stakeholder satisfaction, 2) resource base impacts of the system, and 3) ecosystem impacts of the system. Figure 2.9 (Pearce et al. 2002) shows a triaxial representation of the parameters of technological sustainability, where the state of sustainability for technological systems is defined when the basic needs are met (stakeholder satisfaction), and there are neutral or no impacts related to resource base and ecosystem impacts.

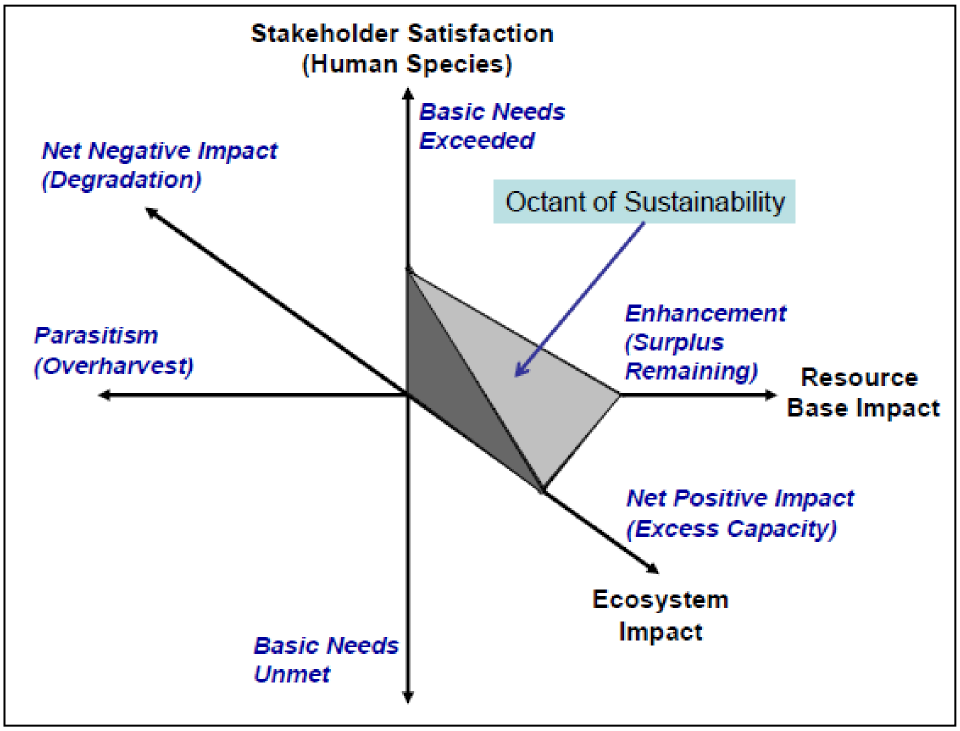

Figure 2.9. Triaxial Represenation of Global Sustainability

Azapagic (2003) proposed a framework to assess and measure sustainability performance for the mining and minerals industry. The framework comprises environmental, social, economic and integrated indicators, with the latter combining two or more dimensions of sustainability into one indicator. The sustainability issues are identified based on all activities in the supply chain from “cradle to grave.”

Criteria and indicators are established for specific goals that are easy to monitor, whereas sustainability progress for one dimension (environment, society, economy) becomes difficult because different goals may embrace the same indicator or criterion. Frameworks such as the SEA and the life cycle assessment, are objective based (Hart, 2006), with the latter one to be considered as a different framework type as we will see next.

Waheed (2009), identifies four more types of sustainability frameworks: a) Influence-based, b) Process-based or stakeholder-based, c) Material flow accounting (MFA), and d) Life cycle assessment.

MFA was developed in Europe, largely at the Wuppertal Institute in Germany, and has been adopted as a methodology by the European Union with respect to its sustainable development program. Material flow analysis is a framework that determines and analyzes the flow of materials and energy in a predefined system. It is an accounting system that captures the mass balances in an economy, where inputs (extractions and imports) equal outputs (consumption and exports, and accumulation and wastes), and thus is based on the laws of Thermodynamics. It is referred to as MFA when performed on a national or regional scale. It accounts for all materials and energy used in production and consumption stages, including the hidden flows of materials that were extracted in the production cycle but which never entered the final products. Indicators and indices are calculated to assess the level of resource intensity of the system, and processes are optimized in such a way that materials and energy are used in the most efficient manner (SSP 2003.)

The Life Cycle Assessment (LCA) framework is one step beyond to MFA as it uses the same principles but also tries to account for the environmental impacts of a technology, product, process or service throughout their life cycles from raw materials extraction through end of life – disposal or recycling. It is referred as cradle to grave or well to wheel approach. A complete literature review on LCA is located in Chapter 3. Another type of LCA is the Life Cycle Cost Analysis (LCCA) where the total cost of a product, service or process is assessed throughout their full life cycle. LCCA considers direct costs as well as environmental impacts, from LCA, expressed in monetary terms.

Nichols et al. (2008) proposed a hybrid-version framework which combines the theme-based and goal-oriented framework properties for application in transportation sustainability. The proposed framework considered the basic elements from the ECMT (2001) sustainability definition to represent the three pillars of sustainability and to develop a set of 14 indicators for transportation assessment.

Bevan et al. (2008), outlined two basic principles when developing a sustainability framework for transportation infrastructure: a) consideration of the full range of solutions that can be considered to address mobility needs for a specific project, and b) grouping of projects into five major objectives which are related to energy reduction, materials resource reduction, environmental impacts reduction, urban communities support and sustainability support during implementation in local level.

Maoh and Kanaroglou (2009) presented a framework and developed a tool to assess urban sustainability by using 21 indicators that represent environmental, social and economic aspects of sustainability. The tool, which assesses different land use scenarios, was developed as an add-on module to a transportation and land use model (ITLUM.)

Zegras (2007) placed the performance-based transportation planning, the sustainable transportation and the role of indicators within a Sustainable Indicator Prism as shown in Figure 2.10 (Zegras 2006.) The top of the pyramid represents the goals and the objectives (e.g., Sustainable Development) which are supported by the indices (e.g., index of sustainable economic welfare), which in turn are built from raw data (e.g., vehicle fleet size) and indicators (e.g., motorization rate.)

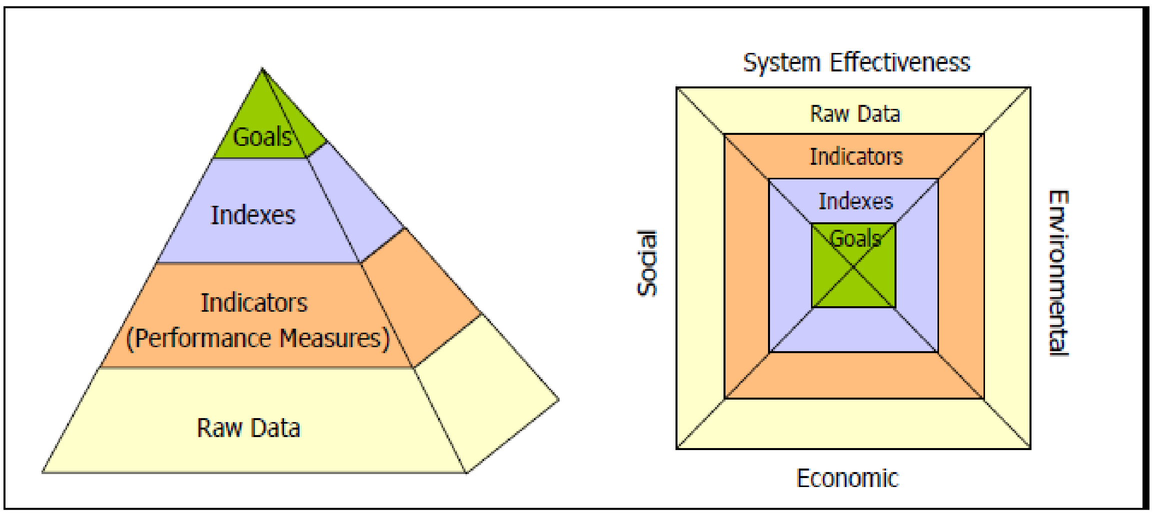

Figure 2.10. Sustainability Indicator Prism

Large scale models for assessing sustainability took place in the E.U. Inputs to the modeling system are policies, GIS and model databases. The E.U. research program PROPOLIS implemented three urban (land use and transport) models in seven European cities to develop and quantify 35 indicators for measuring environmental, social and economic dimensions of sustainability. A decision making support tool was developed to test policies in order to find the optimum sustainable strategies that would improve simultaneously all three dimensions of sustainability (Lautso 2004.)

The four year project, Design and Implementation Support Tools for Integrated Local Land use, Transport and the Environment (DISTILLATE) in U.K., developed and improved tools and techniques to assist in the planning, design and implementation of sustainable transportation and land use strategies and schemes. The tools and techniques were tested by working with local authorities in a series of case studies. For developing the tool, research was conducted about barriers that prevent effective development and delivery of sustainable transportation and land use strategies. It was found that the seven most important indicators for assessing transport sustainability are: public transportation patronage, accessibility, traffic levels, road safety, walking, cycle use and congestion. The program assisted local authorities to establish a set of indicators and concluded that a guidance which would help in monitoring transportation performance would add more value (May 2009.)

The discussion on indicator frameworks in this section shows that given diverse goals, needs and attributes of each system, different frameworks should be considered in sustainability assessment. Hybrid frameworks that do not fall within a specific category, and combine characteristics from different frameworks to meet required objectives can also be developed.

The complex and abstract definitions of sustainability make essential the introduction of a framework that can embrace regional, national or global goals at a disaggregate level and translate these goals into comprehensive assessments for informed decision making. Disaggregated level refers to the separation and consideration of different technological, operational and/or functional characteristics of a system. A suitable framework will set the basis for appropriate performance measures in sustainability assessment. It will support an unbiased analysis, which will provide the basis for subsequent analysis and evaluation.

2.4.2. Sustainability Performance Measures

Not everything that counts can be measured. Not everything that can be measured counts. (Albert Einstein.)

Gudmundsson (1999) defined as indicators "selected, targeted, and compressed variables that reflect public concerns and are of use to decision-makers." An indicator may be either processed or raw data that provides information for the status of a phenomenon solely for the unit of time under interest or for a consecutive time frame. Indicators are used extensively in transportation as a tool for operationalizing sustainability analysis for infrastructure and transportation systems. Their role in transportation planning is shown in Figure 2.11 (Meyer and Miller, 2001.)

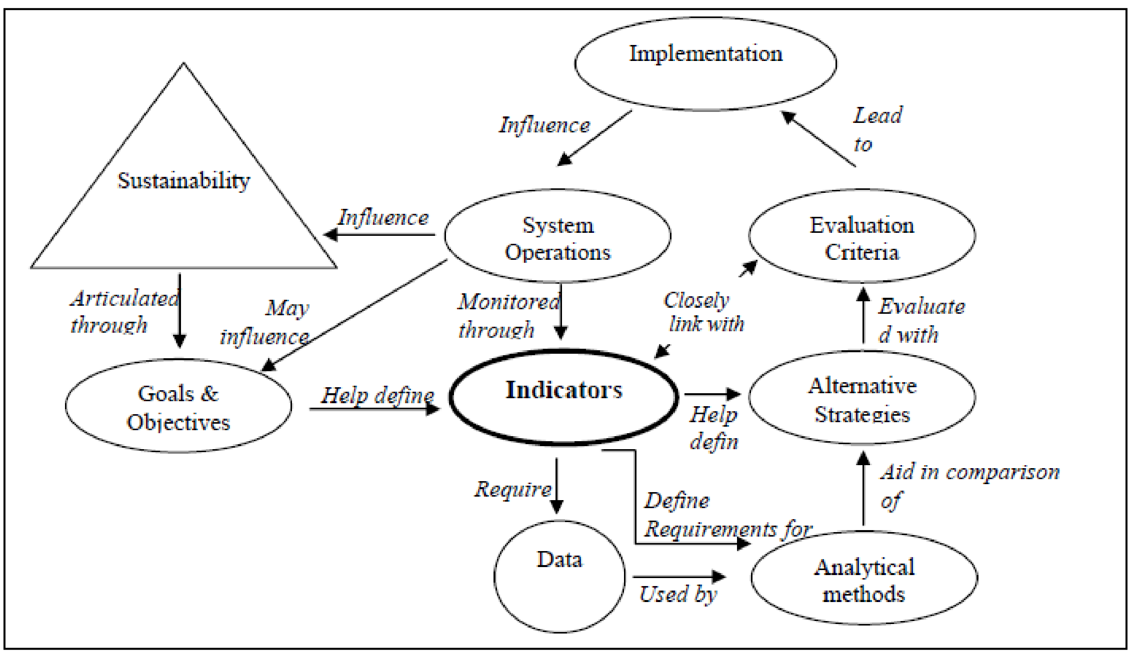

Figure 2.11. The Role of Indicators in the Transportation Planning Process

Basic guidelines related to indicator development were provided by Innes et al. (2000.) They reviewed indicator strategies for communities and concluded that the indicator development process should be different for each city. Given the different number of attributes for each city, the indicators would be influential, and understandable by stakeholders (agencies, experts, citizens), if they are be developed with the participation of the people that are going to use them. An indicator must be associated clearly with a policy or a set of actions, and for it to be defined as influential it will need five to ten years to be developed and linked into policy. The same is valid for every system that aims to develop criteria, indicators or general performance measures to assess sustainability. Developed criteria and indicators should clearly represent aspects of sustainability without overlapping.

Litman (2009) suggested that transportation communities and stakeholders should develop and use "baseline" indicators for comparing transportation impacts. He proposed a set of potential sustainability indicators that fall under different categories and distinguish them into indicators for every situation, project specific applications and application specific applications. Litman (2011) presented conventional transport indicators available in current transportation planning such as level of service (LOS), average traffic speeds, average per capita congestion delay and fatalities. He outlined available indicators for evaluating sustainability from different organizations, projects and communities including the Genuine Progress Indicator developed for Alberta Canada, the U.S.DOT Environmental Performance measures, the Sustainable Transportation Performance Indicators (STPI) project for the Center for Sustainable Transportation, The Environmentally Sustainable Transport (EST) indicators for OECD, the Sustainable Mobility Indicators for the World Business Council Sustainable Development project and EU's Transport and Environment Reporting Mechanism sustainable transportation indicators. Tables 2.1 to 2.3 (Litman 2011) and Tables 2.4 and 2.5 (Miller 2008) present a set of indicators for different dimensions (environment, society, economy, transportation performance) of transportation sustainability.

Incorporation of sustainability in transportation planning has been a topic of research for universities and institutes in the last 10 years or so. The Center for Sustainable Transportation (CTS 2002) used indicators to study whether the transportation sector improves in respect to its adverse impacts on environment and health. In addition, indicators were developed to assess the impact of transportation on environment, economy and society (Maoh 2009, Zietsman et al. 2003), whereas another study added a fourth sustainability dimension, the system effectiveness (Jeon et al. 2008.)

Table 2.1. Economic Indicators of Sustainable Transportation

Indicator	Description
User Satisfaction	Overall transport system user satisfaction ratings.
Commute Time	Average door-to-door commute travel time.
Employment Accessibility	Number of jobs opportunities and commercial services within 30 minute travel distance of residents.
Land Use Mix	Average number of basic services (schools, shops and government offices) within walking distance of homes.
Electronic Communication	Portion of population with Internet service.
Vehicle Travel	Per capita motor vehicle-mileage, particularly in urban-peak conditions.
Transport Diversity	Variety and quality of transport options available in a community.
Mode Split	Portion of travel made by efficient modes: walking, cycling, ridershare, public transit and telework.
Congestion Delay	Per capita traffic congestion delay.
Affordability	Portion of household expenditures devoted to transport, particularly by lower-income households.
Cost Efficiency	Transportation costs as a portion of total economic activity, and per unit of GDP.
Facility Costs	Per capita expenditures on roads, parking, and traffic services.
Cost Efficiency	Portion of road and parking costs borne directly by users.
Freight Efficiency	Speed and affordability of freight and commercial transport.
Delivery Services	Quantity and delivery of delivery services (international intercity courier, and stores that offer delivery)
Commercial Transport	Quality of transport services for commercial users (business, public agencies, tourists, convention attendees.)
Crash Costs	Per capita crash costs.
Planning Quality	Comprehensiveness of the planning process: whether it considers all significant impacts and uses best current evaluation practices.
Mobility Management	Implementation of mobility management programs to address problems and increase transport system efficiency.
Pricing Reforms	Portion of transport costs (roads, parking, insurance, fuel, etc.) that are efficiently priced (charged directly to users.)
Land Use Planning	Applies smart growth land use planning practices, resulting in more accessible, multi-modal communities.

Table 2.2. Social Indicators of Sustainable Transportation

Indicator	Description
User Rating	Overall satisfaction of transport system by disadvantaged users.
Safety	Per capita crash disabilities and fatalities.
Fitness	Portion of population that walks and cycles sufficient for fitness and health (15 minutes or more daily)
Community livability	Degree to which transport activities support community livability objectives (local environment quality.)
Cultural preservation	Degree to which cultural and historic values are reflected and preserved in transport planning decisions.
Non-drivers	Quality of transport services and access for non-drivers.
Affordability	Portion of budgets spent on transport by lower income households.
Disabilities	Quality of transport facilities and services for disabled people.
Non-Motorized Transport	Quality of walking and cycling conditions.
Children Travel	Portion of travel to school and other local destinations by walking and cycling.
Inclusive Planning	Substantial involvement of affected people, with special efforts to insure that disadvantaged and vulnerable groups are involved.

Table 2.3. Environmental Indicators of Sustainable Transportation

Indicator	Description
Climate Change Emissions	Per capita fossil fuel consumption, and emissions of CO_2 and other climate change emissions.
Other Air Pollution	Per capita emissions of "conventional" air pollutants (CO, VOC, NO_x, particulates, etc.)
Air Pollution	Frequency of air pollution standard violations.
Noise Pollution	Portion of population exposed to high levels of traffic noise.
Water Pollution	Per capita vehicle fluid losses.
Land Use impacts	Per capita land devoted to transportation facilties.
Habitat Protection	Preservation of high-quality wildlife habitat (wetlands, old-growth, forests, etc.)
Habitat Fragmentation	Average size of roadless wildlife preserves.
Resource Efficiency	Non-renewable resource consumption in the production and use of vehicles and transport facilities.

Table 2.4. Performance Indicators of Sustainable Transportation (Part A)

Goal	Performance Measures
Increased Transportation Options	Percentage of commuters driving alone to work.
	Number of spaces used at park and ride facilities.
	Travel time and distance to work.
Increased Transportation Options	Ability to get from one destination to another readily, where destinations include jobs, retail and tourist shops, and transit services.
	Percentage of housing units built by location type (e.g., rural growth center, developing area, remaining rural area, or developed area.)
	Percentage jobs/population within particular distance of transit or other modes.
	Miles of bike/ped facilities constructed.
	Number of routes designated as bicycle facilities.
	Number of attractions within a threshold travel time.
	Ration of non-auto to auto travel costs, including travel time and money.
	Access to centers.
	Ratio of jobs to housing.
Improved Quality of Existing Transport Options	Average delay per trip; percentage of person-miles by LOS; real intercity travel time minus (straight line distance divided by the speed limit.)
	Person-hours of delay.
	Satisfaction with transportation options.
Improved Public Services or Economic Growth	Response time for fire, police and rescue and travel time for schools.
	Cost of above municipal services (fire, police, rescue and schools.)
	Reduction in consumer costs attributable to better transport.
	Ratio or actual corridor travel time to free flow travel time.
Protects or Manages Corridors	Number of jurisdictions that protect land adjacent to airports from development.
	Miles of roadway with agreements between state DOT and local government.
	Alignment of strategic highway corridors and land use overlay.

Table 2.5. Performance Indicators of Sustainable Transportation (Part B)

Goal	**Performance Measures**
	Arterials where an access management plan has been established.
	Percent interregional corridor miles with corridor management land use plans.
	Agreement between state and local plans.
Aligns State and Local Efforts	Locations where state and integrated transportation studies are undertaken.
	Jurisdictions with current active local plans.
	Customer satisfaction with coordination.
	Customer /Stakeholder satisfaction rating.
	Transportation projects are listed in the regional transportation plan.
Reduced Land Consumption (and other environmental measures)	Percent of jobs or population in urban centers.
	Population density.
	Geographical expansion of the urbanized area compared to the population growth rate.
	Conversion of undeveloped land.
	Loss of farmland, open space, habitat, forest land acreage or loss of historic resources or of specified/designated visual assets.
	Loss of wetlands.
	Measured O_3, NO_x, CO and estimated (or measured) CO_2 .

2.5. Evaluating Transportation Sustainability Performance

‘‘*Sustainability assessment is. . .a tool that can help decision-makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable.*’’ (Devuyst 2000.)

This section details indicators and dimensions that have been used towards the assessment of sustainable transportation systems. Renne (2009) evaluated Transit

Oriented Development (TOD) sustainability by deploying a survey in five transit stations and by using indicators based on six categories. He argued that since it is difficult to categorize indicators using the three basic categories of sustainable development (environment, society and economy) and since many indicators cross boundaries, six different categories had to be selected. The six categories with the number of proposed indicators for each one shown in the parentheses are:

1. Travel behavior (11)
2. Local economy (11)
3. Natural environment (4)
4. Built environment (21)
5. Social Environment (12)
6. Policy context (3)

The study concluded that the multi-dimensional character of sustainability and the vast number of indicators makes data collection an intricate task. It proposed data collection at regular intervals to track success.

Jeon et al. (2008) suggested 28 indicators representing 13 goals and four sustainability categories for evaluating transportation system sustainability (Figure 2.12.) Eleven of these indicators were quantified to determine environmental, social and economic impacts as well as the sustainability performance of the transportation system for different scenarios in the Metropolitan Atlanta. The study used equal weights for each indicator and sustainability dimension indicating the same relative importance among them. The eleven quantified indicators were aggregated into four dimensions of sustainability indices. Scenarios were evaluated based on a composite sustainability index that was embracing the indices for the four sustainability category (environmental, social, economic impacts and transportation performance.) In a later study, the weights for sustainability indicators and dimensions were determined by using the attribute ranking method (Jeon et al. 2010.)

Sustainability dimension	Goals and objectives	Performance measures
Transportation System Effectiveness	A1. Improve Mobility	A11. Freeway/arterial congestion
		A12. Travel rate (minute/mile)
	A2. Improve System Performance	A21. Total vehicle-miles traveled
		A22. Freight ton-miles
		A23. Transit passenger miles traveled
		A24. Public transit share
Environmental Sustainability	B1. Minimize Greenhouse Effect	B11. CO_2 emissions
		B12. Ozone emissions
	B2. Minimize Air Pollution	B21. VOC emissions
		B22. CO emissions
		B23. NO_x emissions
	B3. Minimize Noise Pollution	B31. Traffic noise level
	B4. Minimize Energy Use	B41. Fuel consumption
Economic Sustainability	C1. Maximize Economic efficiency	C11. User welfare changes
		C12. Total time spent in traffic
	C2. Maximize Affordability	C21. Point-to-point travel cost
	C3. Promote Economic development	C31. Improved accessibility
Social Sustainability	D1. Maximize Equity	D11. Equity of welfare changes
		D12. Equity of exposure to emissions
		D13. Equity of exposure to noise
	D2. Improve Public Health	D21. Exposure to emissions
		D22. Exposure to noise
	D3. Increase Safety and Security	D31. Accidents per VMT
		D32. Crash disabilities
		D33. Crash fatalities
	D4. Increase Accessibility	D41. Access to activity centers
		D42. Access to major services
		D43. Access to open space

VMT: Vehicle miles traveled.

Figure 2.12. Sustainability Goals and Performance Measures

Maoh and Kanaroglou (2009) developed a tool as an add-on module in an integrated and transportation land use model for assessing urban sustainability. Indicators (Figure 2.13) were based on large scale simulation models such as the SPARTACUS, PROPOLIS and PROSPECTS to reflect aspects of environment, society and economy. For the aggregation of indicators into category indices and into a single overall sustainability index, equal weights were assigned among indicators of different sustainability dimensions. The developed indices were used to compare different urban planning scenarios (urban residential intensification, expansion and sprawl.) The same sequence also was followed in this dissertation research.

Pillar	Theme	Label	Indicator	Definition
Environment	*Air pollution*	*AP1*	Greenhouse gases	Level of CO [kg] per 1000 inhabitants
		AP2	Acidifying gases	Level of NOx [kg] per 1000 inhabitants
		AP3	Volatile organic compounds	Level of HC [kg] per 1000 inhabitants
		AP4	Fine particles < 2.5 μm	Level of PM2.5 [kg] per 1000 inhabitants
		AP5	Fine particles < 10 μm	Level of PM10 [kg] per 1000 inhabitants
	Natural Resources	*NR1*	Energy use from fossil fuels	Litters of Gas consumed per 1000 inhabitants
		NR2	Consumption of green space	Arable land area [sq. km] converted to urbanized land
Society	*Health*	*HL1*	Exposure to NO_x from transport	Number of people exposed to harmful levels of NOx per 1000 inhabitants
		HL2	Exposure to CO from transport	Number of people exposed to harmful levels of CO per 1000 inhabitants
		HL3	Traffic injuries	Number of traffic injuries per 1000 inhabitants
		HL4	Traffic deaths	Number of deaths per 1000 inhabitants
	Opportunity	*OP1*	Vitality of CBD	Level of mix in land use in the CBD
		OP2	Residential amenities	Level of mix in land use in the different neighbourhoods of the city
	Accessibility	*AM1*	Accessibility to CBD	Average travel times from all possible locations in the city to City centre
		AM2	Accessibility to services	Average potential accessibility to services
	Commute	*AM3*	Vehicle kilometres traveled	Total VKT per 1000 inhabitants
		AM4	Vehicle minutes traveled	Total VMT per 1000 inhabitants
	Mobility	*AM6*	Congestion index	Average level of congestion in city
Economy	*Cost (dollars)*	*EC1*	Transport investment costs	Total dollars spend on maintaining road infrastructure
		EC2	Transport commuting costs	Overall cost of commuting
		EC3	Transport external costs	Total dollars due to externalities associated with health

Figure 2.13. Indicators for Assessing Urban Sustainability

Zietsman et al. (2006) aggregated 11 sustainability indicators which were aggregated into a single sustainability index for the assessment of two corridors (Table 2.6.) The indicators, which represent five distinct criteria, were grouped into three sustainability categories. The weights for the individual criteria were developed through a Delphi process using four experts in the field of transportation planning. The weights of the indicators were based on the relative costs to society for those indicators.

Table 2.6. Goals and Performance Measures for Corridor Sustainability Assessment

Sustainability Dimension	*Goals*	*Performance measures*
Social	Maximize mobility	Travel rate
	Maximize safety	Accidents per VMT
Economic	Maximize affordability	Point-to-point travel cost
Environmental	Minimize air pollution	VOC, Car on CO and NO_x emissions.
	Minimize energy use	Fuel consumption

Black et al. (2002) proposed a framework that applies different techniques for quantifying indicators of performance and understanding the relationship between urban form and travel. The techniques apply to different scenarios to examine whether suggested policies might be met in the future and to what degree. The framework includes descriptive statistics, spatial mapping, spatial statistics, travel preference functions, regression analysis, time series and travel models. Silva and Ramos (2010) developed an index for urban mobility which is based on a hierarchy of criteria built with data obtained for 11 cities. The index aggregates 87 indicators which are grouped under nine domains and 37 themes. The weights for domains and themes were obtained by using a panel of experts in the fields of urban and transportation planning, mobility and sustainability. Indicators within each theme were assigned equal weights.

EEA efforts to measure and monitor the environmental performance of transportation are described under the title Transport and Environment Reporting Mechanism (TERM.) The TERM program has developed and monitored 40 indicators for seven dimensions of transportation (CST 2005):

- Environmental consequences of transportation
- Transportation demand and intensity
- Spatial planning and accessibility
- Supply of transportation infrastructure and services
- Transportation costs and prices
- Technology and utilization efficiency
- Management integration.

The developed indicators are used to measure the progress towards existing objectives and targets from EU policy documents and various transportation and environmental directives.

Another European program of note, still in development, is entitled Sustainable Mobility, Policy Measures and Assessment (SUMMA.) This program is concerned with sustainable transportation, known as 'sustainable mobility'. The goal of SUMMA is to quantify the concept of mobility in a way that allows performance to be measured. Indicators are proposed for advisory purposes than for operationalizing mobility since it is not certain whether the indicators can be measured or determined. The indicators are presented in five groups (EEA 2004, 2008):

- Indicators of forces driving system change
- System indicators
- Economic outcome indicators
- Environmental outcome indicators
- Social outcome indicators.

Research on incorporating sustainability into transportation planning have resulted in proposals on the development of variables defined as measures, indicators or indices representing elements of sustainability as described in this section. Transport sustainability indicators that measure impacts on mobility, safety and environmental effects are applied mainly to the operation of the transportation system. Effective decision making is based on the results of models that fit models that fit best to the corresponding problem. Sample models are reviewed in the next section.

2.6. Decision Making Methods

Decision making is the task of identifying and choosing alternatives based on values and preferences that are in agreement with the goals, objectives and desires of each plan (Harris 1980.) Selection of a decision making methodology relies upon the level of complexity of each problem and the objectives of the decision maker.

An initial separation between decision making methodologies is made based on the number of criteria for a given problem. For a problem with multiple alternatives and a single criterion, the decision maker has to determine the best alternative by comparing each alternative based on the value or the aggregate value of the criterion (problem optimization.) Hwang and Yoon (1981) classified Multi Criteria Decision Making (MCDM) methods based on the type of information and salient features received from decision makers (Figure 2.15.) Single objective decision making techniques, such as benefit-cost analysis, are not adequate to deal with the complexities and compare effectively issues associated with sustainable transportation (Zietsman et al. 2003.)

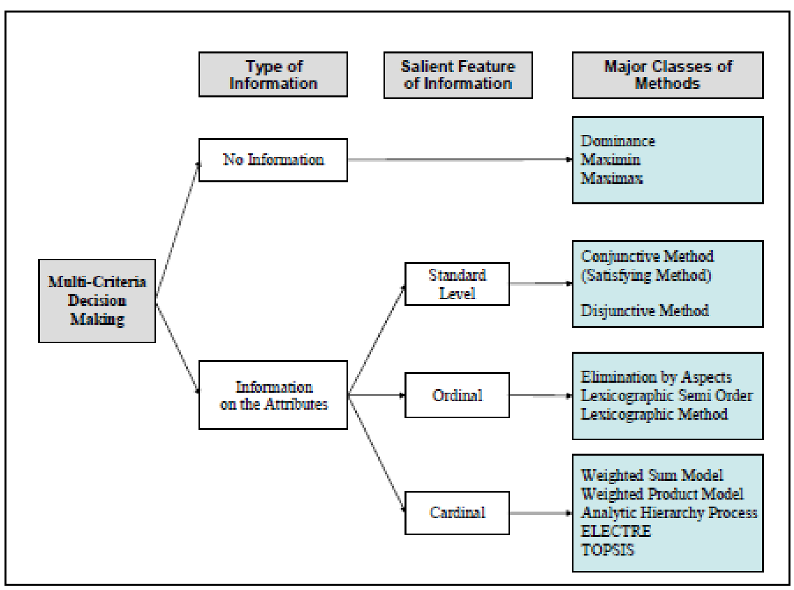

Figure 2.14. Taxonomy of MCDM Methods

The problems that involve multiple criteria and alternatives (such as the ones associated with sustainable transportation) are defined as MCDM problems. In a MCDM problem, weights (w_1, w_2,…, w_n) are assigned to criteria to account for their relative importance. Weights can be assigned directly by the decision maker, or by a group of experts (e.g., Delphi method), or can be determined by a methodology, such as cluster or factor analysis. The multi criteria decision process is shown in Figure 2.16 (Pohekar and Ramachandran 2009.) The different methods are described as follows.

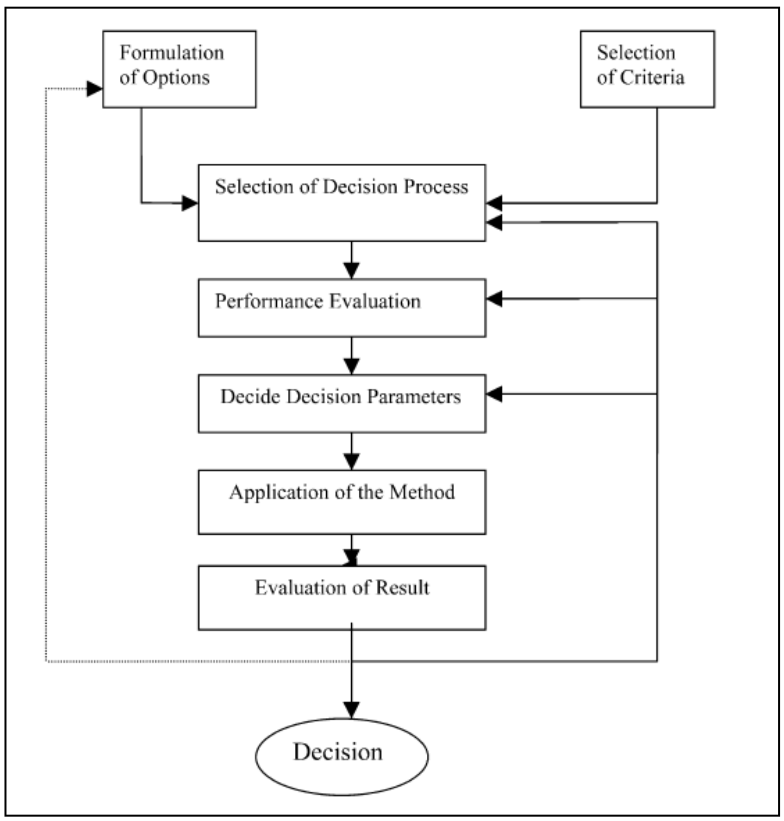

Figure 2.15. Multi-Criteria Decision Process

Several methodologies exist and have been adopted in the transportation sector for assessing projects and plans. Selective MCDM techniques include:

- Bayesian decision making

- Entropy technique
- Expected value method
- Goals achievement method
- Utility function based methods: Multi Attribute Utility Theory (MAUT), Simple Multi Attribute Rated Technique (SMART), Analytical Hierarchy Process (AHP), Weighted Sum Model (WSM), Weighted Product Model (WPM)
- Outranking methods (ELECTRE, PROMETHEE I and II, REGIME analysis.)

The most widely used methodologies are the AHP, the MAUT and the outranking method. Polatidis et al. 2006 recommend MCDM methods to be applied in renewable energy planning (sustainable development,) to avoid ending up an assessment of alternatives with an infeasible alternative.

WSM is the earliest and most commonly used method. The assumption that governs this model is the additive utility assumption (i.e., the total value of each alternative equals to the sum of products given from equation 2.1.) Utility values are determined for each alternative by using equation 2.1 (Triantafphylou and Mann 1989.) The value of alternative A_i with assigned weight w_j for each criterion j can be expressed mathematically as:

$$U_i = \sum_{j=1}^{n} w_j v_{ij} \qquad i = 1, \dots, m \tag{2.1}$$

Where: U_i is the utility of alternative i

w_j is the weight of the *jth* criterion

v_j is the actual value of criterion j for alternative i.

WSM can be applied in problems with different alternatives and one criterion, where the units that describe the criterion are the same for all alternatives. For multi criteria problems, equation 2.1 cannot be applied, because the addition of different units will not provide credible results and comparisons. Addition among criteria with different units is performed only after the different measurement units are normalized into a dimensionless scale and the utility V_i for each alternative is estimated by equation 2.1.

$$V_i = \sum_{j=1}^{n} w_j N_{ij} \qquad i = 1, \dots, m \tag{2.2}$$

Where: N_{ij} is the normalized value of criterion j for alternative i.

WSM was used by Maoh and Kanaroglou (2009) and Jeon et al. (2007) to evaluate sustainability of transportation system based on the assessment of sustainability criteria. They used WSM to aggregate normalized values of criteria into sustainability category indices and an overall sustainability index per studied scenario. WSM was applied in this dissertation research to aggregate normalized indicators for competing alternatives as described in Chapter 5 and 6.

The difference between WSP and WPM is that instead of addition the total score of each criterion is estimated by multiplication. The utility value for each alternative is estimated by multiplying a number of values, one for each criterion. Each criterion's value is raised to the power equivalent to the relative weight of the corresponding criterion. Criteria with different measurement units can be used in the WPM since values are multiplied. The value of an alternative A_i is given by:

$$V_i = \prod_{j=1}^{n} v_{ij}^{w_j} \tag{3}$$

WPM requires all criteria values to be greater than zero, since zero value assigned for a given criterion will return zero utility for alternative *i*. For this reason WPM is not used often in sustainable transportation assessment including this dissertation research.

The basis of MAUT is the utilization of utility functions in every decision problem. Utility functions can be applied to transform the raw performance values of the alternatives against diverse criteria to a common, dimensionless scale. MAUT seeks to measure the different values that are assigned to each alternative by aggregating those values across the dimensions through a weighting procedure (Zietsman et al. 2003.) In MAUT, the raw performance values, which present a more preferred performance, obtain a higher utility value.

There are six steps for determining the utility value or the desirability, of the design, (Olson 1996.)

1. Identify significant design attributes and generate alternative designs
2. Verify relevant attribute conditions or bounds
3. Use a lottery to determine the designer's preference
4. Evaluate Single Attribute Utility (SAU) function and trade-off preferences
5. Combine SAUs into a Multi-Attribute Utility function (MAU)
6. Rank the alternatives and select the alternative with the highest MAU value.

Zietsman et al. 2003 adopt the MAUT approach to evaluate sustainability performance of two corridors, with and without criteria weights. The criteria weight development was performed through a Delphi process using four experts in the field of transportation planning.

The basic idea of the Outranking method is that an alternative A_i outranks A_j if on a great part of the criteria A_i performs at least as good as A_j, while its worse performance is still acceptable for the other criteria. After having determined for each pair of alternatives whether one alternative outranks another, these pair-wise outranking assessments can be combined into a partial or complete ranking. The outranking method may not render the best alternative directly. A subset of alternatives can be determined such that any alternative not in the subset be outranked by at least one member of the subset. The aim is to make this subset as small as possible (Fulop 2006.) Outranking methods do not permit tradeoffs between different dimensions as the MAUT methods do.

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) uses the outranking principle. In this method first a preference function is structured for every criterion. Then the alternatives are compared in pairs to the preference function and the outcomes of these comparisons are presented in a matrix that can be evaluated. The last step of the general process includes the determination of thresholds and the estimation of preference functions for every actor. After that point the ranking is completed in two parts. In the first part PROMETHEE I is applied for partial ranking and the second part applies the PROMETHEE II to complete the ranking of alternatives (Tsoutsos et al. 2009.) Tsoutsos et al. (2009) assessed the economic, technical, social and environmental characteristics of a set of energy planning alternatives, by choosing the PROMETHEE I and II methods to translate preferences into weights.

AHP is the formalization of a complex problem using a hierarchical structure (Yoon and Wang 1995.) Elements at a given hierarchical level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The scale of 1 to 9 is used to assess the intensity of preference between two elements. Ratio scale is used for weighting quantifiable and non-quantifiable elements. The method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives is obtained. The estimated weight vector is then multiplied with the weight coefficient of the criterion that was used for pair wise comparison. The final weight coefficients reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy (Pohekar and Ramachandran 2009.)

AHP has been used in several sustainability and transportation studies. Levine (1996) used a modified APH for intelligent transportation system planning in Oackland County. Paez and Currie (2008) adopted the APH method to develop an Integrated Transport Plan in Melbourne by considering six criteria and 45 values for each criterion, resulting in a 270 individual pairwise decisions. They enriched the AHP method with a new process called the Advanced Relative Voting System. Graymore et al. (2009) obtained weights for 13 sustainability indicators for developing an index of regional sustainability. AHP was used to derive weights of indicators by the prioritization of their impact to overall sustainability assessment of the company. Kranjnc and Glavic (2005) used the AHP for generating a model for integrated assessment of sustainable development.

Problems, which involve a number of alternatives and criteria, and decisions under uncertainty, are approached by using the Bayesian decision theory and the Bayesian Networks. Bayesian decision theory provides a mathematical model for making engineering decisions in the face of uncertainty – where the consequences of a decision depend on some factor that is not known with certainty. This factor is often called the "state of nature." By recognizing this uncertainty, the true state of nature can be expressed probabilistically. A decision can then be formulated based on the alternatives and the probabilities of the states of nature (Zietsman et al. 2003.) Bayesian Networks are developed in the Artificial Intelligence community for representing uncertainty in intelligent systems. The general form of a Bayesian Network is a directed acyclic graph that constitutes the network structure and represents qualitative information on causality among variables. The causal graph is a representation of causal knowledge within a probabilistic framework (Wiboonsak and Peng 2004, Fusco 2003.) For example, a Bayesian Network could represent the probabilistic relationships between transportation modes and criteria that influence user choice such as cost, comfort and safety. Given the criteria, the network can be used to estimate the probabilities of choosing each mode. Bayesian methods and networks have been used in urban sustainable mobility (Fusco 2003) and in the development of a framework for MCDM that was applied to a mode choice problem (Wiboonsak and Peng 2004.)

2.7. Summary

While sustainability is a very broad concept that can be applied to any system, there is not a standard definition that underlies the development of a holistic and comprehensive framework that can be used in the assessment of transportation systems.

While there is no standard sustainability definition, framework or indicators for assessing a transportation system, there are common characteristics and objectives such as the mobility of people and goods, accessibility and safety within environmental limits that are shared between public and private organizations. An extensive study by Jeon and Amekudzi (2008) on sustainability initiatives in North America, Europe and Oceania revealed that a standard definition of transportation system sustainability is unavailable. Additionally, several sustainability models have been developed to show dimensions or fundamental components of sustainability and its interactions. The dimensions that are used to draw conclusions on the sustainability performance of a transportation system are usually environment, society and economy while the performance of the system in some occasions supplements the assessment.

The review on sustainability frameworks and performance measures identified that a dynamic sustainability framework that is implemented in different systems should be adjustable to the goals and objectives of decision makers. Hybrid frameworks, that combine different framework characteristics, are used to provide comprehensive sustainability indicators. Regarding the development of sustainability indicators, Innes et al. (2000), conclude correctly that the process for developing indicators should be different for each city. This is true, because given a different amount of attributes for each system, the developed indicators would be influential, and understandable by stakeholders (agencies, experts, citizens) only if they account for these different attributes. Utilization of integrated sustainability indicators that usually cross boundaries places a hurdle in understanding the sustainability performance of a transportation system.

Meanwhile, a number of studies have focused on the evaluation of sustainability for transportation systems around the world, with many of them targeting on the development of decision making support tools to test policies in order to find the optimum sustainable strategies. Multiple criteria decision making (MCDM) methods found to be the most appropriate ones for application in transportation planning and decision making. This study uses the weighted sum model (WSM) due to its simplicity and capability to combine various measures with different dimensions.

CHAPTER 3

LIFE CYCLE ASSESSMENT

No one person can make a pencil. Vast numbers of people participate in making the materials that become a pencil: the wood, the brass, the graphite, the rubber for the eraser, the paint and so on. Then go back another step, to the people who make the saws and machinery that are used to make the materials that go into a pencil. And before that, people mine iron to make the steel that makes the machines that make the materials that go into a pencil. It's all without central direction, without these people even knowing they are all working ultimately to make pencils. Thousands of people mining, melting, cutting, assembling, packing, selling, shipping -- and yet you can buy pencils for a few pennies each. That's spontaneous order, and it's replicated with every product we buy, no matter how complex. (John Stossel, 2011.)

3.1. Introduction

This chapter is the second part of the literature review. It first defines life cycle assessment (LCA), it outlines its basic phases and briefly summarizes fields of application. The basic models of LCA are presented and the ones which are used in this study are explained in detail. In order to understand the boundaries of LCA's application, the general limitations of the methodology are listed. LCA has been used extensively in the transportation sector for a variety of transportation components. A literature review is given of applications of LCA on major transportation components, related to vehicles, fuels, and materials. The last section of this chapter presents attempts to incorporate LCA in sustainability assessment and the state-of-the-art in different fields.

3.2. Life Cycle Assessment

As environmental and energy preservation concerns rapidly increase, performance of technology has become an important issue in its development, operation, maintenance, upgrade and disposal stages. LCA is a methodology first used in the 1960s in U.S. by Harold Smith to estimate energy requirements for the production of chemical products (Ciabrone 1997.) Later LCA was used by the Coca Cola Company to compare the environmental effect of different containers. Since then, LCA has been used in many different fields such as agriculture, water technologies, construction, domestic product production, energy production, transportation and so on, mainly to estimate energy requirements and generation of emissions for one or more products.

LCA has been defined as a "cradle-to-grave" approach for assessing industrial systems. The term "life cycle" refers to the most energy and emissions intense activities in the product's lifetime from its manufacture, use, and maintenance, to its final disposal or recycling. "Cradle-to-grave" includes the extraction and collection of raw materials from the earth to create the product and ends when all materials are returned back to the earth. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.) Additionally, LCA assists decision-makers to select the product or process that will result in the least possible impact to the environment (EPA 2006.)

The LCA methodology became part of the ISO 14000 environmental scheme standards and according to these standards LCA is carried out in four phases, as shown in

Figure 3.1, of which the third phase is divided into three subcomponents (ISO 2006, Consoli et al. 1993, Stripple 2001):

- Goal and scope definition
- Inventory analysis
- Impact assessment
  - ✓ Classification
  - ✓ Characterization
  - ✓ Valuation
- Interpretation - Improvement assessment

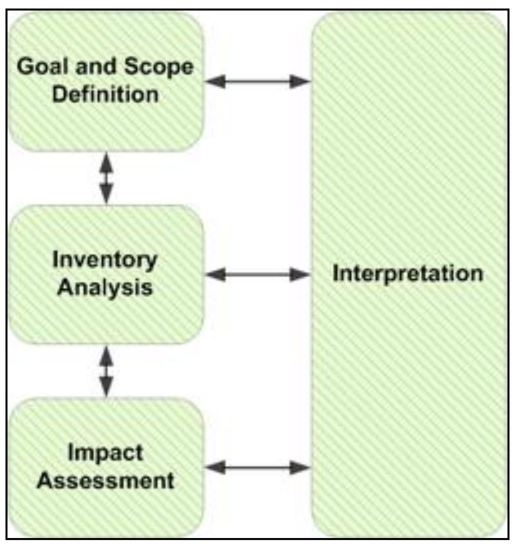

Figure 3.1. LCA Framework

3.2.1 Goal and Scope

A LCA study starts with an explicit statement of the goal and scope, which sets out the context of the study and explains how the results are going to be used. The ISO standards require the goal and the scope of a LCA to be clearly defined and consistent with the intended application. In the scope of a LCA the following items shall be considered:

- The functional unit, which defines what precisely is being studied and provides a reference to which the inputs and outputs can be related
- System boundaries
- Assumptions and limitations
- Allocation methods and procedures
- Impact categories chosen

The goal of the study, the data and time availability as well as the required accuracy of the results determine the number of stages that will be included in the scope of the study. As mentioned above, LCA includes all four stages of a product or process life cycle: raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management. The four stages of a product or process life cycle are (EPA 2006):

Raw Materials Acquisition – The life cycle of a product begins with the removal of raw materials and energy sources from the earth. Transportation of these materials from the point of acquisition to the point of processing is also included in this stage.

Manufacturing – During the manufacturing stage, raw materials are transformed into a product. The product is then delivered to the consumer. The manufacturing stage consists of three steps: materials manufacture, product fabrication, and filling/packaging and distribution.

Use, Reuse, Maintenance – This stage involves the consumer's actual use, reuse, and maintenance of the product. It includes energy demands and environmental wastes from both product storage and consumption. The product or components of the product may need to be reconditioned, repaired or serviced so that it will maintain its performance.

Recycle/Waste Management – When the consumer no longer needs the product, the product will be recycled or disposed. The recycle/waste management stage includes the energy requirements and environmental wastes associated with disposition or recycling of the product.

3.2.2 Inventory Analysis

The inventory analysis describes the material and energy flows to and from the system for different life stages. All of the life stages require different inputs and generate different outputs. Typical inputs, outputs and life cycle stages that are considered in the LCA are shown in Figure 3.2 (EPA 1993.) The life cycle inventories are required for the environmental comparison of different products and processes. The result of the inventory analysis is a summary of all inputs and outputs related to the "functional unit" selected by the user.

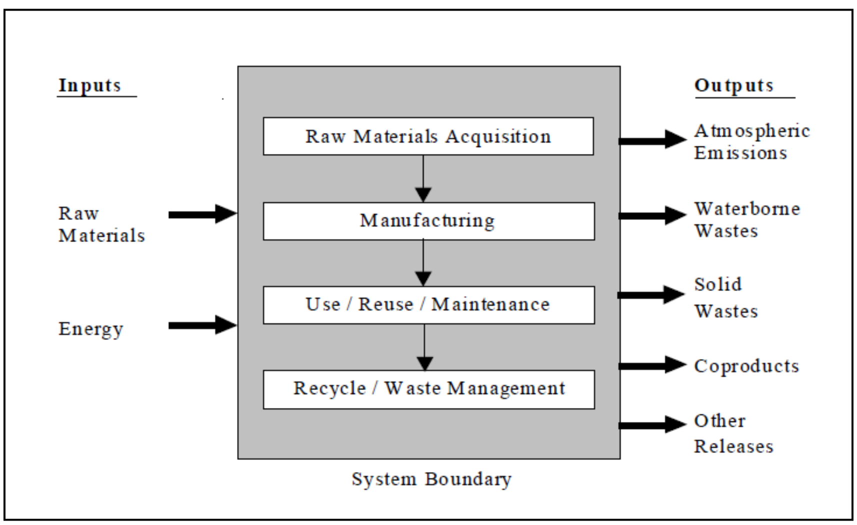

Figure 3.2. Life Cycle Stages

3.2.3 Impact Assessment

Classification – In the classification sub-phase, the environmental impacts, the inputs and outputs of the inventory analysis are described and grouped. Impact category selection is dependent on the objectives of the study. Selective impact categories suggested by Finnveden (1993) include resource consumption, energy and material, land, water, health effects, toxic effects, physical and psychological effects, global warming, ozone depletion, acidification and eutrophication.

Characterization – In the characterization sub-phase, the inventory parameters are sorted, aggregated and assigned to a specific impact category. For example, in the classification, the parameters that contribute to global warming are described. In the characterization, the contributions of the different parameters to global warming are aggregated in CO_2 equivalents. The most common life cycle impact categories are shown in Figure 3.3 (EPA 2006.)

Valuation – In the valuation sub-phase, different impact categories are compared with each other by using one of many possible methodologies, into common equivalence units that are then summed to provide an overall impact category total. There is currently no consensus regarding which methods can be used and when. Other optional valuation elements such as normalization, grouping, and weighting may be conducted depending on the goal and scope of the LCA study. ISO 14044:2006 generally advises against weighting, stating that "weighting, shall not be used in LCA studies" (Trusty 2010, pp.2.)

Impact Category	Scale	Examples of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents; uses multi-media modeling, exposure pathways.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill or other land modifications	Land Availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

Figure 3.3. Commonly Used Life Cycle Impact Categories

3.2.4 Interpretation - Improvement Assessment

In the interpretation – improvement assessment phase the results from the inventory analysis and impact assessment are summarized. The outcome of this phase is a set of conclusions and recommendations for the study. According to ISO 14040 (2006), the interpretation should:

- Identify significant issues based on the results of the LCA study
- Evaluate the study considering completeness, sensitivity and consistency checks
- Include conclusions, limitations and recommendations.

3.3. LCA Models

Different LCA methods, such as the cradle to grave, cradle to gate, cradle to cradle, well to wheel, life cycle cost analysis (LCCA), the Economic Input-Output LCA (EIO-LCA) and hybrid methods that combine the strengths of two methods into a new method, have been developed to enhance product analysis based on the set requirements. The models that are used in this study are described below.

3.3.1 Well-to-Wheel

Well-to-wheel (WTW) is the specific LCA used for transport fuels and vehicles. Pioneer transportation WTW analyses began in 1980. Early studies were motivated primarily by electric vehicles (EVs) and current studies are motivated primarily by fuel cell vehicles (FCVs.) The analysis is separated into phases entitled "well-to-pump", or "well-to-tank", and "pump-to-wheel", or "tank-to-wheel", or "plug-to-wheel" (Wang 2003.) The first phase incorporates the feedstock or fuel production, processing and fuel delivery or energy transmission, while the second phase deals with the vehicle operation itself. The WTW analysis is commonly used to assess total energy consumption, or energy conversion efficiency and emissions impact of marine vessels, aircraft and motor vehicle emissions, including their carbon footprint, and the fuels used in each of these modes. Figure 3.4 (Argonne Laboratory 2010) illustrates the stages for the well-to-wheel method for the two phases: "well-to-pump" and "pump-to-wheel" (Brinkman 2005, CEC 2007.)

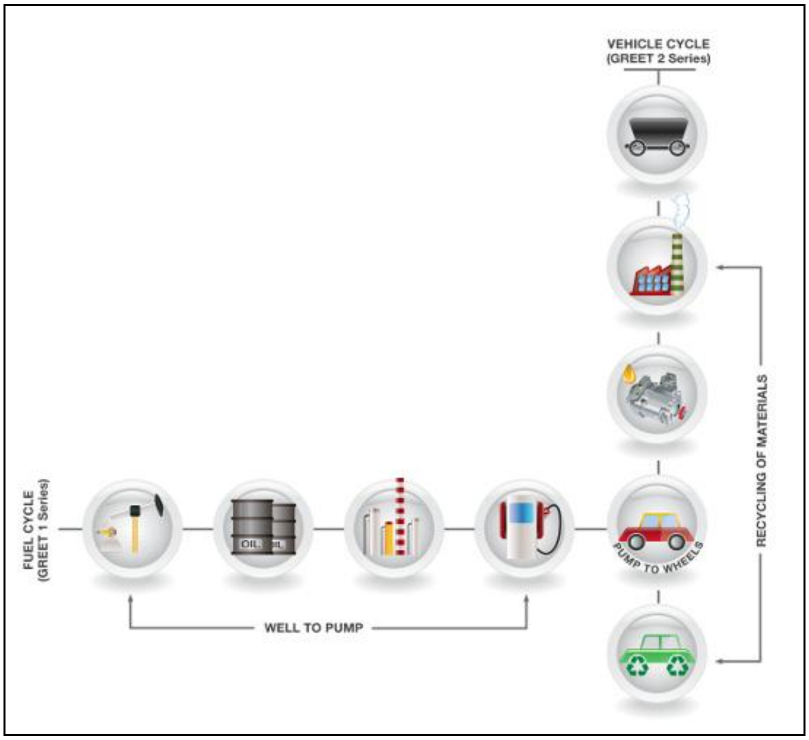

Figure 3.4. Vehicle Well-to-Wheel Method Stages

3.3.2 Economic Input-Output Life Cycle Assessment

The EIO-LCA was developed by Carnegie Mellon University's Green Design Institute. Researchers at Carnegie Mellon have developed an approach based on models of industrial activity (input-output tables) and pollution discharge data. The traditional economic input-output model (matrix) indicating economic transactions between industries can be appended with information on emissions to the environment. The appended model can estimate how increased demand for output from one sector influences the output of pollutants to the environment (Hendrickson et al. 2006.) The resulting software tool, called EIO-LCA allows for economy-wide LCAs at a fairly coarse (aggregate) scale and provides environmental and economic assessment of products, services or processes. EIO-LCA is described in Chapter 4.

3.4. LCA Limitations

LCA utilization can be resource and time intensive, depending upon how thorough an LCA should be. Data availability can greatly impact the accuracy of the final results. Additionally, LCA is not designed to provide a final product or process choice as it cannot determine which product or process is the most cost effective or works the best. Therefore, the information developed and provided by a LCA study should be used as one component of a more comprehensive decision making process (EPA 2006.) LCA methodology has been criticized for the following issues:

- Environmental effects for all life-cycle stages are not known
- It is difficult to compare different types of effects
- The amount of data required to analyze even simple products is enormous
- Data collection is an intensive task as many of the life cycle stages involve proprietary processes

It is difficult to know where to draw the boundary around the analysis. Often fixed capital investments are neglected and only deal with the operation of these in the analysis.

3.5. Transportation Life Cycle Assessment

As described in Chapter 2, LCA has been used extensively in the transportation sector due to its important and pervasive impacts on environment. There is an emerging consensus that current regulations that are based on tailpipe emissions need to change in order to account for the full environmental costs and benefits of introduced transportation modes. Furthermore, other parts of modes, such as tires, seats and infrastructure have improved their environmental performance, since production, maintenance and operation requirements have significantly become less energy demanding. Studies that have used the LCA methodology to analyze the energy and environmental impacts of transportation components include passenger car tires, lithium-ion batteries for electric vehicles, road pavements and so on (Continental 1999, Gauch et al. 2009, Volkswagen 2008, Kaniut 1997, Wang et al. 2007.)

A comprehensive assessment of an urban transportation mode includes the analysis of the vehicle and the corresponding infrastructure during its lifetime. A life cycle analysis of a mode provides a complete assessment rather than an operation only-based assessment that neglects important stages of environmental performance of urban transportation modes (such as manufacturing and maintenance.) The latter provides incomplete results in transportation planning. The LCA methodology has been used extensively by government agencies, private companies and research centers to assess the environmental performance of vehicles, fuels and road infrastructure.

In road infrastructure, the LCA has been used to study the environmental performance of different materials and methods used in paving, reinforcement and construction processes. Stripple (2001) developed a LCA for the road construction process. He analyzed three different types of road surface materials: concrete and two types of asphalt depending on the construction process. The LCA methodology followed partly the standard (goal definition and inventory analysis), which was developed by SETAC (Society of Environmental Toxicology and Chemistry) and explained in section

3.2. The study concluded that the total energy consumption in construction, operation and maintenance for a 1 km long road during a period of 40 years of operation is approximately 23 TJ for asphalt surface, and around 27 TJ for a concrete surface. Minor energy differences were found for different methods for asphalt. It is worth noting that the operation of the road (electrical energy for street lighting and traffic lights) makes up a large part of the total energy consumption. The electrical energy was estimated to be around 12 TJ.

Additionally, the LCA methodology has been used extensively for the assessment of alternative transportation fuel types due to the increased sources of energy and to the requirements set by agencies. U.S. EPA analyzed the life cycle GHG emissions for a range of biofuels, currently expected to contribute significantly to meet the volume mandates of Energy Independence and Security Act (EISA) through 2022, including those from domestic and international sources. As mandated by EISA, the GHG emission assessments must evaluate the full life cycle emission impacts of fuel production including both direct and indirect emissions, as well as emissions from land use changes (EPA 2009a.)

The WTW methodology became a promising tool for the environmental and energy assessment of alternative fuel vehicles (AFV) since 1990s due to its utilization in the assessment of electric vehicles. Wang (1999) studied various fuel/technology combinations for passenger cars to estimate their fuel-cycle energy and emission requirements. The study concluded that fuel cell vehicles (FCV) and hybrid electric vehicles (HEV) achieve large reductions in total energy due to the improved vehicle fuel economy and large GHG reductions achieved when gas-based methanol was used and when advanced engine vehicle technologies were operating with renewable fuels.

Another broad study on fuel types and different powertrain systems that supports these findings was commissioned by General Motors. Brinkman (2001) presented the study that was conducted on 75 fuel pathways and 15 advanced and conventional powertrain systems. The study found that FCV powered by clean gasoline offer greatly reduced GHG emissions compared with current powertrains/fuels, whereas methanol FCV do not offer significant advantages. Conventional natural gas does not offer significant benefits compared with ICEVs. Finally the lowest GHG emissions were offered by renewable fuels and nuclear power. The study was updated in 2005 to address additional pollutant emissions, including volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM_{10}), and sulfur oxide emissions (SO_x.) They also included the latest powertrain systems such as hydrogen internal combustion engines (ICEs.)

WTW calculations were based on a fuel cycle model developed by Argonne National Laboratory (ANL): the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. The simulations in the study showed that, in general, fuel production and vehicle operation are the two key WTW stages in determining energy use and emissions results. The fuel production stage usually has the largest energy-efficiency losses of all well-to-tank stages. This is true for production of gasoline, diesel, hydrogen, Fischer-Tropsch diesel, ethanol, methanol, and electricity. For the vehicle operation stage, the most significant factor in determining WTW results was found to be the fuel consumption of the vehicle technologies when modeled for 2010 (Brinkman et al.

2005.) Other WTW studies have been conducted on biofuels (Wang 2009), plug-in hybrid electric vehicles (Elgowainy et al. 2009) and alternative fuel vehicles (Lane 2006.) Detailed LCA studies on electric vehicles in ANL were first conducted by Cuenca et al. (1998) and Humphreys et al. (1999.)

Additional studies supported the argument that operation related emissions are strongly related to other life cycle stages, followed by fueling related emissions. DeCicco et al. 2004 state that tailpipe emissions, which result from fuel combustion, account for 68% of an average vehicle's life cycle CO_2 emissions. Petroleum refining process, crude oil extraction and transportation, and gasoline distribution account for 21% of life cycle CO_2 emissions. The remaining 11% of an automobile's CO_2 emissions occur during manufacturing (make materials and assemble car parts.) Less than 1% of an automobile's life cycle energy consumption and CO_2 emissions occur during "end-of-life" processing (i.e., scrap, etc.), but the end-of-life impacts can be much larger for other pollutants, such as mercury and other toxic materials (Keoleian et al. 1997.)

Delucchi (1991) performed a comprehensive and extensive life cycle analysis of various transportation fuels, including electricity generation, to estimate the GHG emissions and energy consumption from several fuel cycles (primary energy recovery and on-vehicle fuel combustion.) His study included changes in the land use caused by biofuels production, energy and emissions during manufacturing and maintenance of vehicles as well as manufacture of materials used in major energy facilities. He concluded that coal based fuels increased GHGs, whereas moderate reductions occurred from using natural gas based fuels and major reductions occurred from utilization of woody biomass-based ethanol. In addition, GHGs were nearly eliminated when solar energy via electricity or hydrogen was used and GHGs were greatly reduced when nuclear energy via electricity or hydrogen was used. An expanded life cycle study from Delucchi (2003), which included more emissions sources, vehicles and modes reported that fuel cycle GHG emissions from EVs are much lower than from a gasoline vehicle due to the increased EV efficiency.

A recent study by Bandivadekar et al. (2008) assessed different technologies of light-duty vehicles and fuels that could be developed and commercialized by 2035. They compared options for reducing fuel consumption and GHG emissions, by focusing on petroleum based fuels. The study showed that reduction of fuel consumption is feasible in the stated horizon but in the near term alternative fuels derived from raw materials such as oil sands, coal and natural gas to replace petroleum do not show the potential to reduce GHGs significantly.

Volkswagen compared a gasoline model (Golf VI) with 1.6-liter engine with its predecessor model (Golf V), and diesel model with 2.0-litre TDI with a predecessor model (Golf V 1.9 TDI.) In both occasions the new model was released in 2008 and its predecessor in 2003. The study concluded that the greatest advances have been made in the areas of global warming potential (i.e., less GHG emissions), acidification (i.e., less CO_2 emissions), and photochemical ozone (summer smog) (i.e., less CO and VOC emissions) creation potential. In other respects, such as water, soil eutrophication and ozone depletion, the assessed cars had in any case very little impact. It emerged that these improvements were primarily due to reduced fuel consumption and reduction in environmental impact at the fuel production stage. The reduction in fuel consumption is the direct result of improvements related to the engines and transmissions as well as improvements in the areas of light-weight design, aerodynamic drag and rolling resistance and the energy consumption of electrical components (Volkswagen 2008.)

As mentioned, current studies are motivated primarily by FCV. Many studies included in their assessment FCVs and internal combustion engine vehicle ICEV. Zamel and Xianguo (2006) estimated the life cycle energy requirements and GHG emissions of an ICEV and a FCV in Canada by considering the recycling stage and four different methods of hydrogen production. They concluded that total emissions and energy consumption from the FCV are much lower than the total emissions generated by the ICEV, and utilization of recycled materials in manufacturing process can reduce energy consumption and CO_2 emissions almost in half.

A life cycle analysis of vehicle materials may provide useful information for the evaluation of tradeoffs involved in fuel-economy policies. Consideration of lighter materials, such as aluminum, to replace steel parts and of recycled materials to replace virgin materials are the latest trends in vehicle manufacturing. The dominant material that is used in vehicle manufacturing is steel. The percentage of other materials such as aluminum and plastics has increased steadily in an attempt to make cars lighter and to improve fuel economy. Figure 3.5 (Volkswagen 2008) indicates a sample material composition of material shares for a Volkswagen Golf VI 2.0 TDI DPF.

LCA can compare the energy and emissions saved from light materials vehicles with increased fuel economy, with the extra energy and emissions generated in the production of the lighter materials (Delucchi and Salon 2003.) Stodolsky et al. (1995) assessed the life cycle energy and fuel use impacts of aluminum intensive passenger cars and trucks. They projected energy savings from 2005 to 2030 and they concluded that there are net energy savings that may increase further if wrought aluminum is recycled back to wrought aluminum.

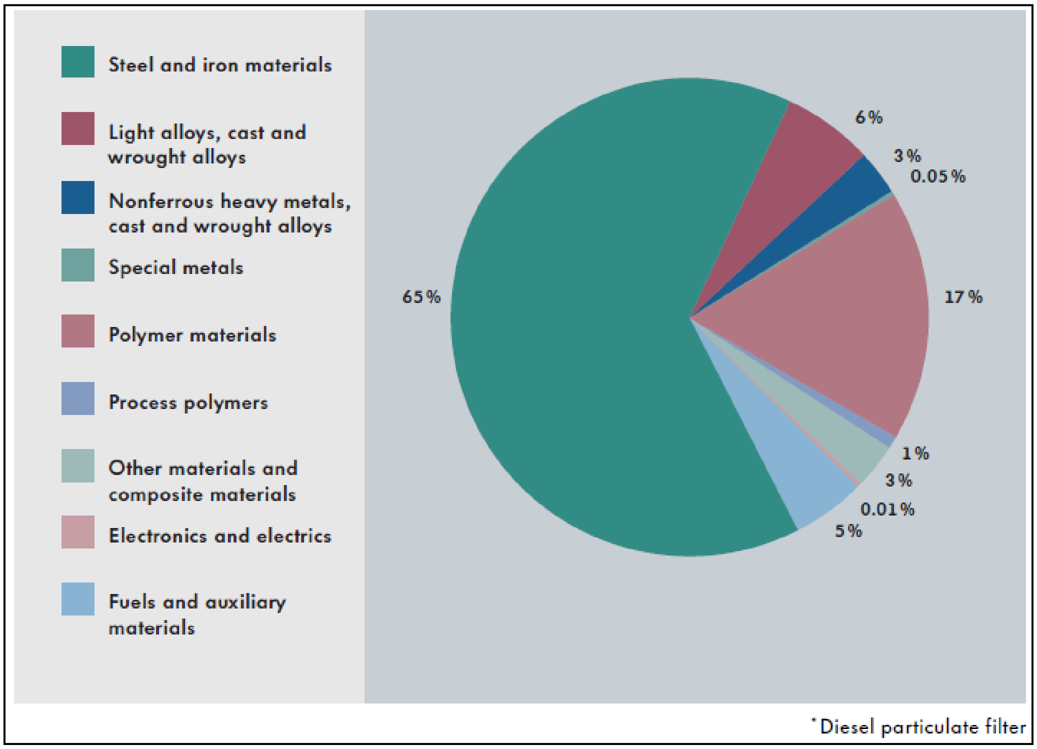

Figure 3.5. Sample Material Composition of a Golf VI 2.0 TDI DPF

The need to study the environmental and energy impacts from vehicles, fuels and materials over their life cycle resulted in a life cycle emissions model (LEM.) The LEM developed by Delucchi and Salon 2003 to estimate the life cycle end-use emissions in countries other than the U.S. The model estimates urban air pollutants and GHGs from the complete fuels and materials life cycle of a variety of transportation modes, fuels, and technologies. The LEM parameters describe inputs and outputs of fuel-conversion processes (e.g., crude oil refining to gasoline), the efficiency of fuel use by motor vehicles (e.g., fuel economy in urban driving), emissions from motor vehicles (e.g., g/mi of particulate matter), and so on.

3.6. Life Cycle Sustainability Assessment

In an attempt to incorporate sustainability and environmental aspects of products and services in a tool or model, the LCA methodology combined with other methodolgies can provide a strong foundation for decision making. Limited literature describes these attempts to incorporate other tools in order to include economic and social aspects in an analysis, thus covering the three pillars of sustainability.

Zamagni et al. (2006) worked on the the E.U. 6th framework CALCAS (Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability) to identify how to increase the efficacy of sustainability decision making. The program attempted to go beyond the shortcomings and limitations of currrent LCA, which has environmental focus only and addresses potential environmental impacts.

Based on the work done on CALCAS, Heijuns at al. (2010) focused on the development of a framework that incorporates different models for environmental analysis with the option of a broader scope to include economic and social aspects.

Klöpffer (2008) suggested a conceptual formula that a life cycle sustainability assessment (LCSA) is a LCA, a life cycle cost (LCC) and an social life cycle assessment (SLCA), done in a consecutive way.

A life cycle sustainability assessment of fuels was performed by Zhou et al. (2006.) The assessment evaluated different fuel types based on four indicators, with each indicator representing a sustainability category. The life cycle cost indicator represented economy, the global warming indicator represented environment, the net energy yield indicator represented energy and the non-renewable resource depletion potential indicator represented renewability.

3.7. Summary

In this chapter the four phases to carry out a LCA and the four stages of a product or process life cycle LCA were discussed. The four stages of a complete product or process LCA (1) raw materials acquisition, (2) manufacturing, (3) use, reuse, maintenance, and (4) recycle - waste management, are used in a complete LCA of a product or process. To enhance product analysis based on the set requirements and project limitations, LCA embraces different models, such as the cradle to grave, the WTW and EIO-LCA.

LCA has been used extensively in the transportation sector to determine the life cycle environmental impacts of transportation infrastructure and other components such as batteries, tires, seats and so on. The WTW model has been used specifically to compare the life cycle environmental performance of vehicle technologies and different types of fuels. There are only a handful of studies that describe the incorporation of the LCA methodology in sustainability assessment. The LCSA is expanded and enriched by the research of this dissertation as the most promising methodology for sustainable transportation assessment.

CHAPTER 4

METHODOLOGY

Attempts to incorporate sustainability into transportation planning have resulted in research on the development of variables defined as measures, indicators or indices representing elements of sustainability. Transportation sustainability indicators that measure impacts on mobility, safety and environmental effects are applied mainly to the operational stage of a transportation system. However, major components of a transportation system are omitted in this approach, including infrastructure construction, vehicle manufacture, maintenance and disposal. Past studies that assessed transportation sustainability, considered only personal vehicles or all modes present on a section of a network by using aggregated measures to evaluate sustainability performance. The aggregation of transportation performance measures limits one of sustainability's roles in transportation planning, which is to assist agencies in evaluating new transportation modes that are proposed for introduction in a network.

The objective of this chapter is to present a methodology that develops and uses a comprehensive sustainability framework for the life cycle assessment (LCA) of any system. It is then modified to perform a life cycle sustainability assessment (LCSA) of transportation modes. The last stage of the methodology is the development of a tool that has the potential to incorporate sustainability into transportation planning.

This chapter provides a methodology for the development of a life cycle sustainability framework (LCSF). Figure 4.1 shows the structure and contents of Chapters 4 and 5.

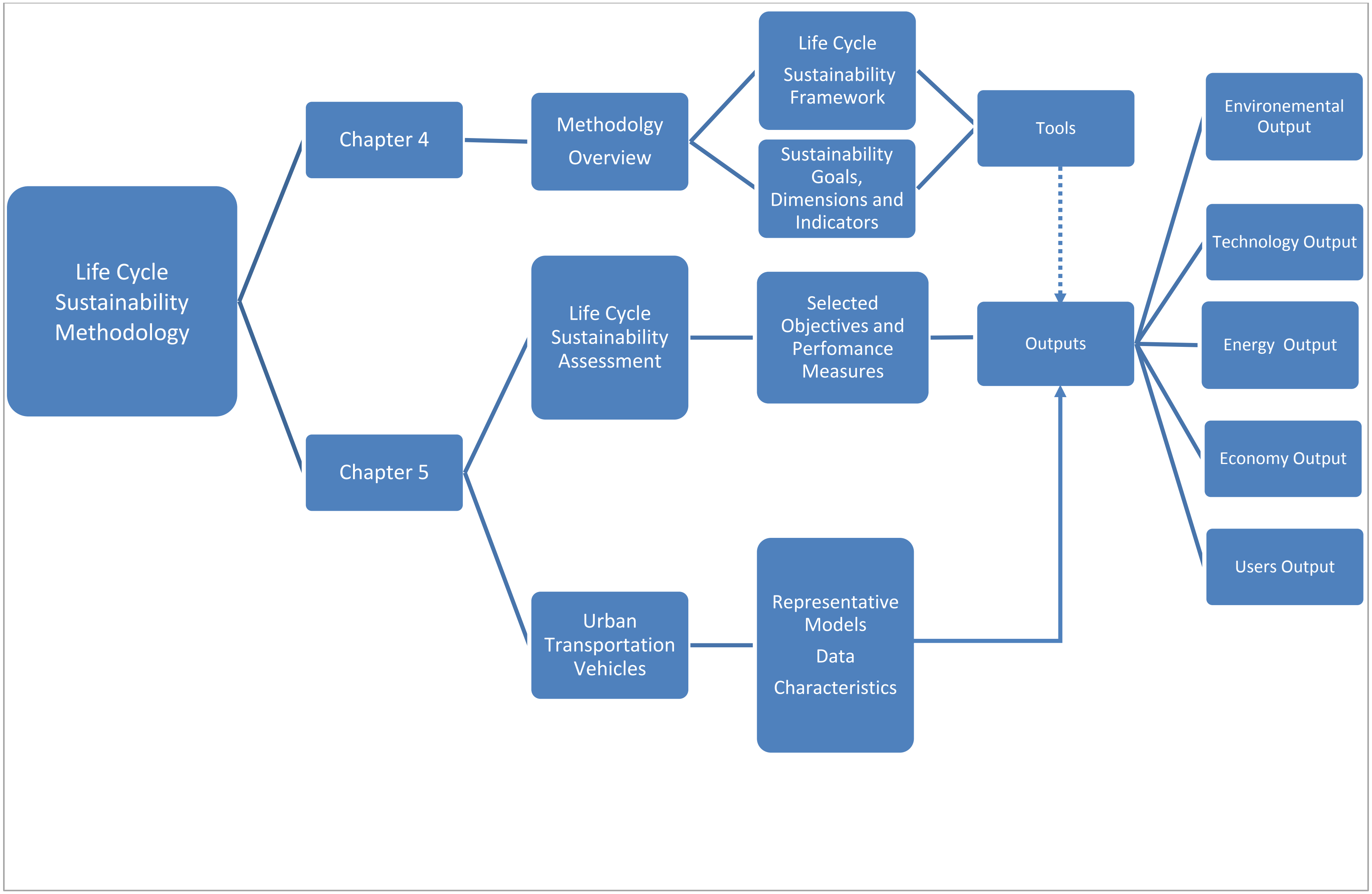

Figure 4.1. Presentation of Components of Transportation Sustainability

4.1. Methodology Overview

Traditional sustainability assessment utilizes the three major sustainability dimensions (i.e., Environment, Society and Economy) for incorporating sustainability into a system. Proposed indicators used for the evaluation of system outcomes usually cross sustainability boundaries and place a hurdle for understanding system impacts on sustainability and thus developing effective policies and strategies to promote sustainability. System impacts to sustainability are usually of most interest during the operation stage, however they are not limited only to this stage. The literature revealed a significant number of studies that evaluate the environmental life cycle impact of transportation components. Some studies focus on the life cycle cost assessment (Hackney and Neufville 2001) and others on societal life cycle impacts (Ogden et al. 2004, Hackney and Neufville 2001.) Generally, there is a tendency to provide more accurate and comprehensive system analysis by accounting for a system's sustainability impacts over its entire life cycle.

Incorporation of sustainability into any system (e.g., city, community, structure, process, service and product) can be performed comprehensively and effectively by first developing a sustainability framework that captures system needs (i.e., what it seeks to achieve) and translate them into goals that endorse overall sustainability. Second, the determined goals are used to define system sustainability dimensions. These dimensions are significant for the creation and preservation of the system over its life cycle. Lastly, the system is disaggregated into major components. The dimensions and the component characteristics are used to incorporate and modify performance measures that will evaluate the system and the progress towards set goals. Such an approach leads to the development of specific indicators that capture life cycle sustainability performance of the component, rather the whole system (i.e., vehicle versus transportation system) which is a more complex task. Upon quantification of component indicators, the results can be aggregated based on the number or the size of components in the system to perform an overall sustainability evaluation. The basic steps for incorporating sustainability into a system are shown in Figure 4.2.

The LCSF can be applied in the sustainability assessment of any system and for this dissertation is adjusted to assess sustainability in transportation. Different vehicle technologies and types are used in the LCSA of urban transportation modes. In order to investigate the ability of LCSF to include more modes as those become available, an additional mode (i.e., carshare) was included in the LCSA, after the initial set of transportation modes was assessed.

The goal of the methodology is twofold: theoretical and practical. The theoretical part of the methodology sets the foundations of the analysis by a) developing a LCSF, decomposing a transportation system into its components, and b) identifying and modifying indicators for each sustainability dimension to assess a set of urban transportation vehicles over their life cycle. The practical part of the methodology implements suitable tools to quantify the proposed set of indicators identified in the theoretical part to compare urban transportation vehicles in a sustainability context.

In this research the methodology enables comparisons by mode (e.g., private vehicle with technology X vs. bus), by system (e.g., BRT vs. Light Rail), by corridor (e.g., HOT lanes vs. Mass Transit), and by area (comparisons of sections in the same city, or comparisons among cities or metro areas.) The results are technology and policy sensitive, thus useful for both short and long term planning.

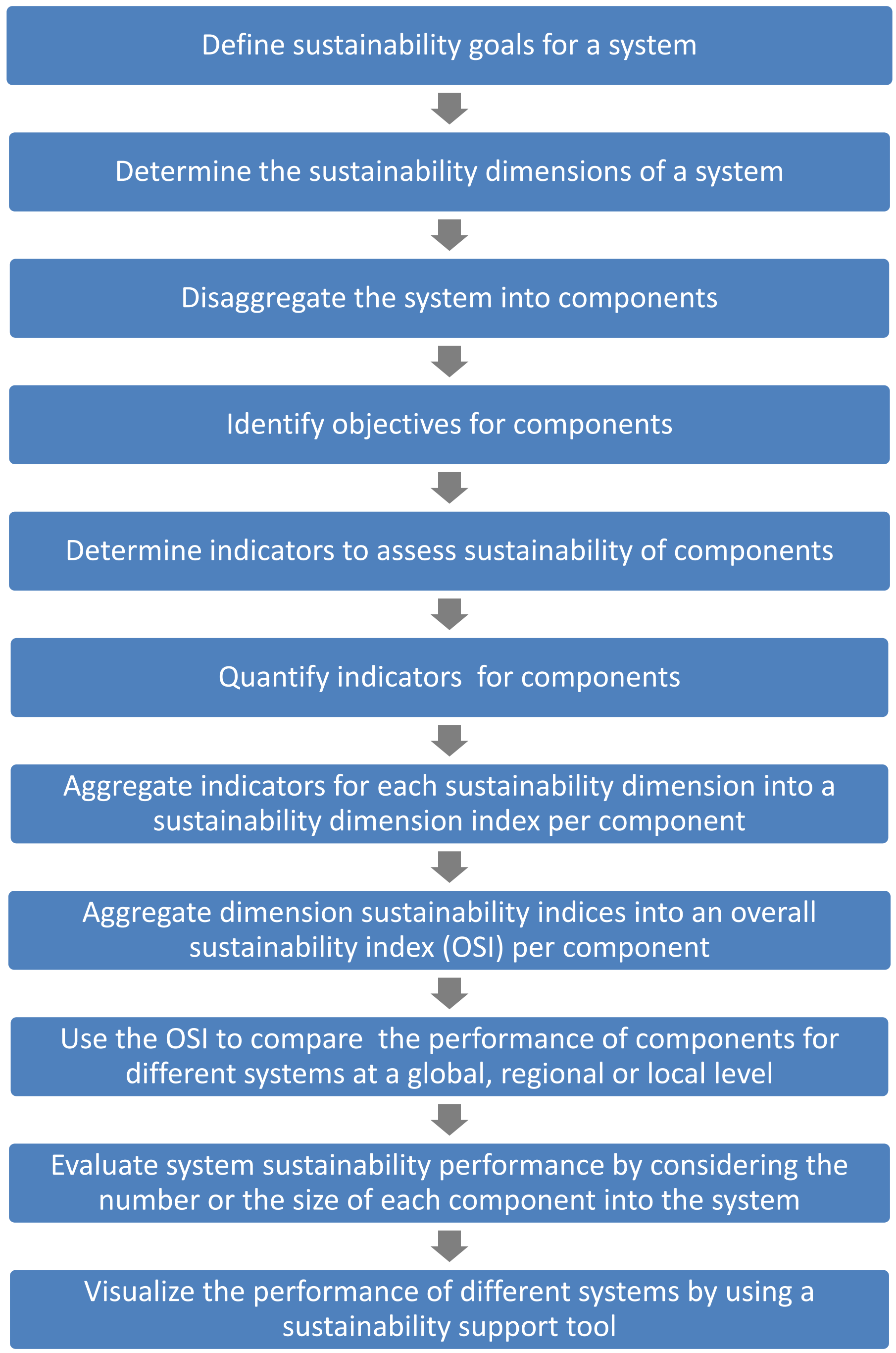

Figure 4.2. Integration of a Sustainability Framework

The LCSF is used to assess the sustainability performance of 11 vehicles. The vehicles are ranked based on their performance per sustainability dimension and overall. The attainment sustainability ratio is used to estimate percentage of overall sustainability achievement. Results are aggregated for three metropolitan areas to assess their transport sustainability performance using the vehicle population and mix in each area. A regular pentagon is used to summarize the outputs. Each corner of the pentagon represents one of the sustainability dimensions used and illustrates sample scores of metropolitan areas for each sustainability dimension, as shown in Figure 4.3. This sustainability support tool can be used by decision makers in transportation planning to demonstrate potential tradeoffs between the sustainability dimensions for different choices or transportation policies (e.g., effect of EVs based on corresponding policies.)

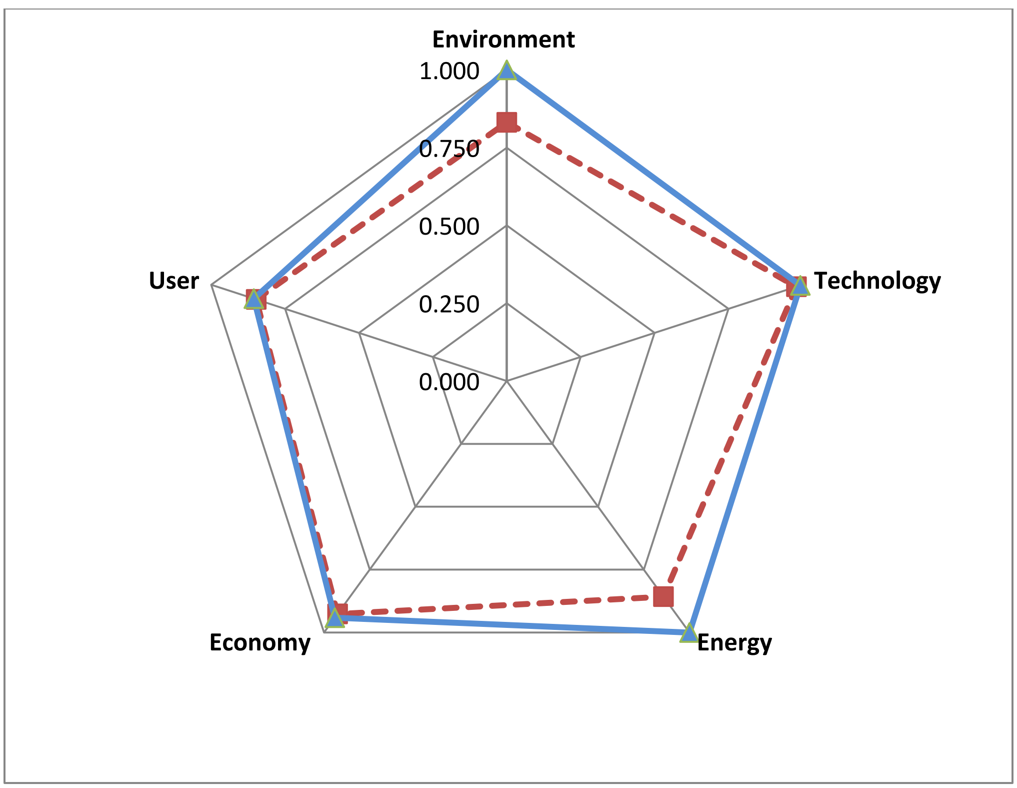

Figure 4.3. Sustainability Support Tool with Sample Cities

4.2. Life Cycle Sustainability Framework

A traditional transportation mode evaluation is based on demand and supply comparisons, cost and benefit evaluations, financial risks analysis, and cost-effectiveness analysis. Recent assessments tend to focus on detailed energy requirements and emissions during operations. In short, there are multiple view points for assessing modes of transportation due to their important and pervasive impacts to society and economy, both positive and negative. Importantly, a long-term sustainability-based comprehensive framework for the monitoring and the life cycle assessment of any urban transportation mode does not exist. This research effort attempts to close this void in the state of the art starting with a framework that has its foundations in the over-arching principle of sustainability. In this context, vehicle type refers to vehicle propulsion technology (e.g., internal combustion or electric), and basic functionality (car/van, light-truck, bus, heavy truck, etc.)

The accelerated development and introduction of vehicles with alternative propulsion systems within the next years compel a detailed breakdown of vehicle components and characteristics for the proper understanding of their performance and impacts over their entire life cycle. Disaggregation per vehicle type in a transportation network and life cycle sustainability assessment may lead to more accurate planning and policy making. Vehicle disaggregation per type in this dissertation refers to the consideration of different technological, operational and/or functional vehicle characteristics.

LCA is a useful tool in the analysis of transportation components due to the detailed energy and emissions outputs that it can generate. Most LCA studies in transportation focus on vehicle emissions due to the significant impact they have on climate change and air quality. Transportation sector operations embrace a number of supporting components such as plants, companies and agencies, which consume vast amounts of energy and emit pollutants during their lifetime. Life cycle assessment of these associated components within an integrated framework becomes impracticable. As a result, detailed LCAs focus usually on the vehicle and its parts. The supporting components of transportation sector and the components that are assessed in the present LCA are presented in Tables 4.1 and 4.2.

Table 4.1. Supporting Components of Transportation Sector, Applicable to Conventional and Alternative Vehicle Technologies (Part A)

	ITEM	Vehicle Technologies: Gasoline & Diesel Based	PHEV EV	FCV
Manufacturing	Mining plant, equipment and transportation	•	•	•
	Fiber sources, transportation and process	•	•	•
	Manufacturing components plants (tires, metal parts, liquids, battery, textiles)	•	•	•
	Raw material recovery and extraction [1]	•	•	•
	Material processing and fabrication	•	•	•
	Vehicle component production	•	•	•
	Vehicle assembly	•	•	•
	Transportation of raw and processed material for each process step	•	•	•
	Assembly components plant	•	•	•
	R&D for vehicle components	•	•	•
	Feed, insure, accommodate workers	•	•	•
	Dispatch vehicles by boat, rail, truck	•	•	•
	Dealerships	•	•	•

Table 4.2. Supporting Components of Transportation Sector, Applicable to Conventional and Alternative Vehicle Technologies (Part B)

	ITEM	Vehicle Technologies: Gasoline & Diesel Based	PHEV EV	FCV
Fuel	Extraction platforms (onshore/offshore)	•	-	-
	Electricity generation plant (nuclear, coal)	-	•	-
	Hydrogen plant	-	-	•
	Feedstock (including feedstock recovery, transportation and storage)	•	•	•
	Fuel (including fuel production, transportation, storage and distribution)	•	•	•
	Transportation and storage	•	•	•
	Refining plant	•	-	-
	Renewable energy infrastructure	-	•	-
	Hydrogen pipelines	-	-	•
	Electricity cables and poles	-	•	-
	Protecting overseas oil resources	•	-	-
Operation	Gas stations	•	-	-
	Swap stations	-	•	-
	Hydrogen stations	-	-	•
	Diesel stations	-	-	-
	Insurance, driving license, taxes	•	•	•
	Washing stations	•	•	•
	Parking structures and equipment	•	•	•
	Traffic lights and signs	•	•	•
	Department of Transportation	•	•	•
	Road lights	•	•	•
	Running, start up, tire, brake, idling	•	•	•
	Charging stations	-	•	-
	Operation centers	-	•	-
	Stops, shelters, ticket machines	-	-	-
	Operation centers	-	-	-
Maintenance	**Vehicle disposal and recycling process**	•	•	•
	Vehicle maintenance	•	•	•
	Maintenance shops	•	•	•
	Dismantling facilities	•	•	•
	Scrap yards	•	•	•
	Shredding facilities	•	•	•
	Steel mills	•	•	•

[1] Items in bold are assessed in the present study.

In developing a life cycle sustainability framework (LCSF), the generic structure components of a transportation system and the restrictions that may be faced in its development and implementation are considered. Note that the LCSF is suitable for the analysis of various systems of urban infrastructure including utilities, with minor modifications for specific applications. These specifications refer to the indicators that must be developed to assess the system. The seven sustainability based goals are identified and are proposed as the most essential for the development, implementation and preservation of a system. The goals seek to 1) minimize environmental impact, 2) minimize energy consumption, 3) maximize and support a vibrant economy, 4) maximize users' satisfaction, 5) maximize technology performance to help people meet their needs, 6) comply with legal framework, and 7) comply with local restrictions of each place. The LCSF consists of seven fundamental dimensions that are captured by the proposed goals governing transportation systems: (1) Environment; (2) Technology; (3) Energy; (4) Economy, (5) Users and other stakeholders, (6) Legal framework, and (7) Local restrictions.

The LCSF acts as a filter (in the form of an "optical prism") that decomposes the components of a transportation mode to reveal its sustainability spectrum. According to the proposed framework, a prism is used as a visual representation of the hierarchy of the four first dimensions to depict the dependence that each category exerts on the next one (Figure 4.4.)

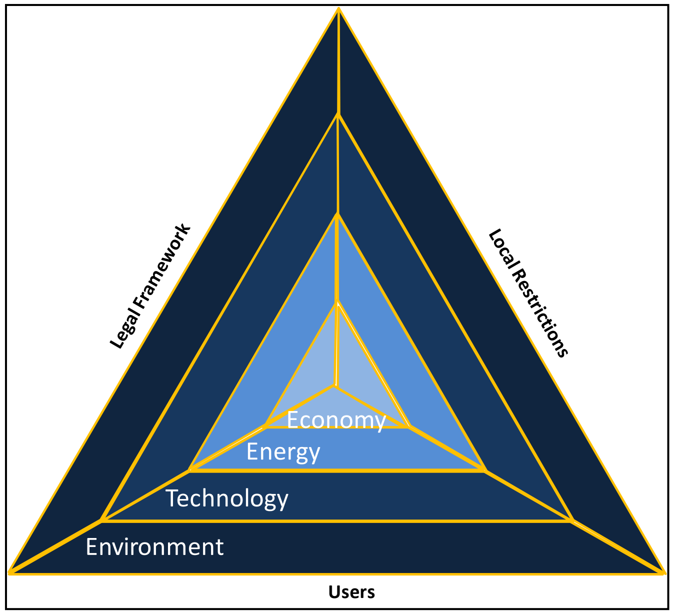

Figure 4.4. Sustainability Decomposition Prism

The four layers of the prism represent the essential components for the development of a system. The three sides of the prism represent the three dimensions that restrict the system's creation, implementation and acceptance. These restrictions are imposed by the community. The International Council on Systems Engineering (ICSE 2000) defines a system as an integrated set of elements that accomplishes a defined objective. In this context this framework can be used to appraise almost any system such as a wastewater treatment plant, a power plant, a public transit system, HOT lanes and so forth.

The proposed dimension layout discloses that all activities and processes occur within the broad environmental limits and they are part of it. Technology is the human creation of tools and crafts to affect environment. Energy was taken outside of environment and was made a separate layer due to its importance and complex participation in the development, operation and maintenance of urban systems. Energy is a part of technology, but only a fraction of technology components are related to the creation and distribution of energy. Not all technologies that are related to energy are directly related to the economy, thus sustainable economy should be developed within specific limitations, imposed by the environment and the availability of technology and energy.

The three dimensions placed on the sides of the prism, imply that even if a system is planned or created and characterized as sustainable compared with another system in terms of the first four dimensions, the latter three dimensions (users, legal framework, and local restrictions) may not allow its implementation or, in general, control its deployment (e.g., final alignment and station location of a proposed rail system). Each dimension of the LCSF is described in section 4.3.

The seven sustainability dimensions form the sustainability prism, which is the visualization element in decomposing systems with respect to sustainability. The prism property to refract light into its spectral colors is used to explain decomposition of a system into its sustainability spectrum.

The LCSF is applied in transportation and for that it is modified by using the characteristics of urban transportation modes. An urban transportation mode is a system that is composed of components and attributes; with the components being the vehicle and the infrastructure. The system operator controls the supply of capacity for each mode and the traveler decides which mode to use based on the performance of each mode, in conjunction with the trip's characteristics. The attributes of vehicles and infrastructure are: Manufacture, fuel, operation, and maintenance for the first, and construction, fuel, operation, and maintenance for the latter. Consideration of such attributes becomes important when different technologies and fuel types are used.

In this dissertation, the sustainability prism is used to decompose transportation modes. To understand the concept of the prism, each component-attribute (i.e., vehicle-operation) is represented by a beam that passes through the Sustainability Decomposition Prism where it is refracted (Figure 4.5 and 4.6.) Each component-attribute beam exits the prism separated into its sustainability spectrum (e.g., vehicle-operation-environment, vehicle-operation-technology, etc.)

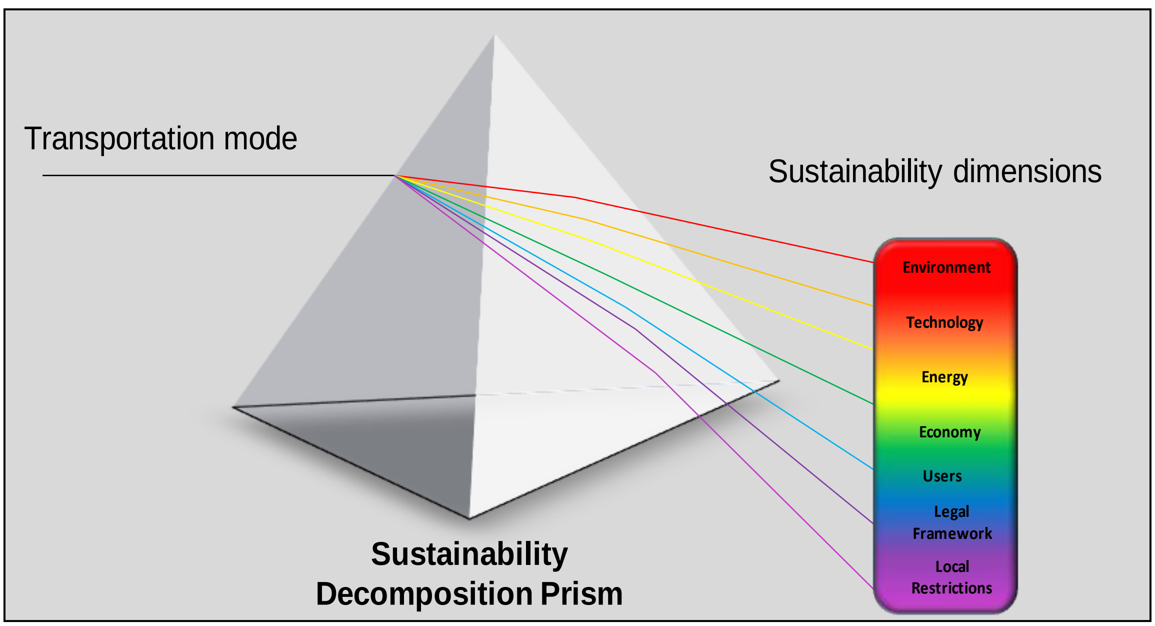

Figure 4.5. Sustainability Decomposition Prism and Dimensions

The combination of sustainability dimension and system component is used to identify and develop indicators. The dimension and indicators of the LCSF are discussed in the following section.

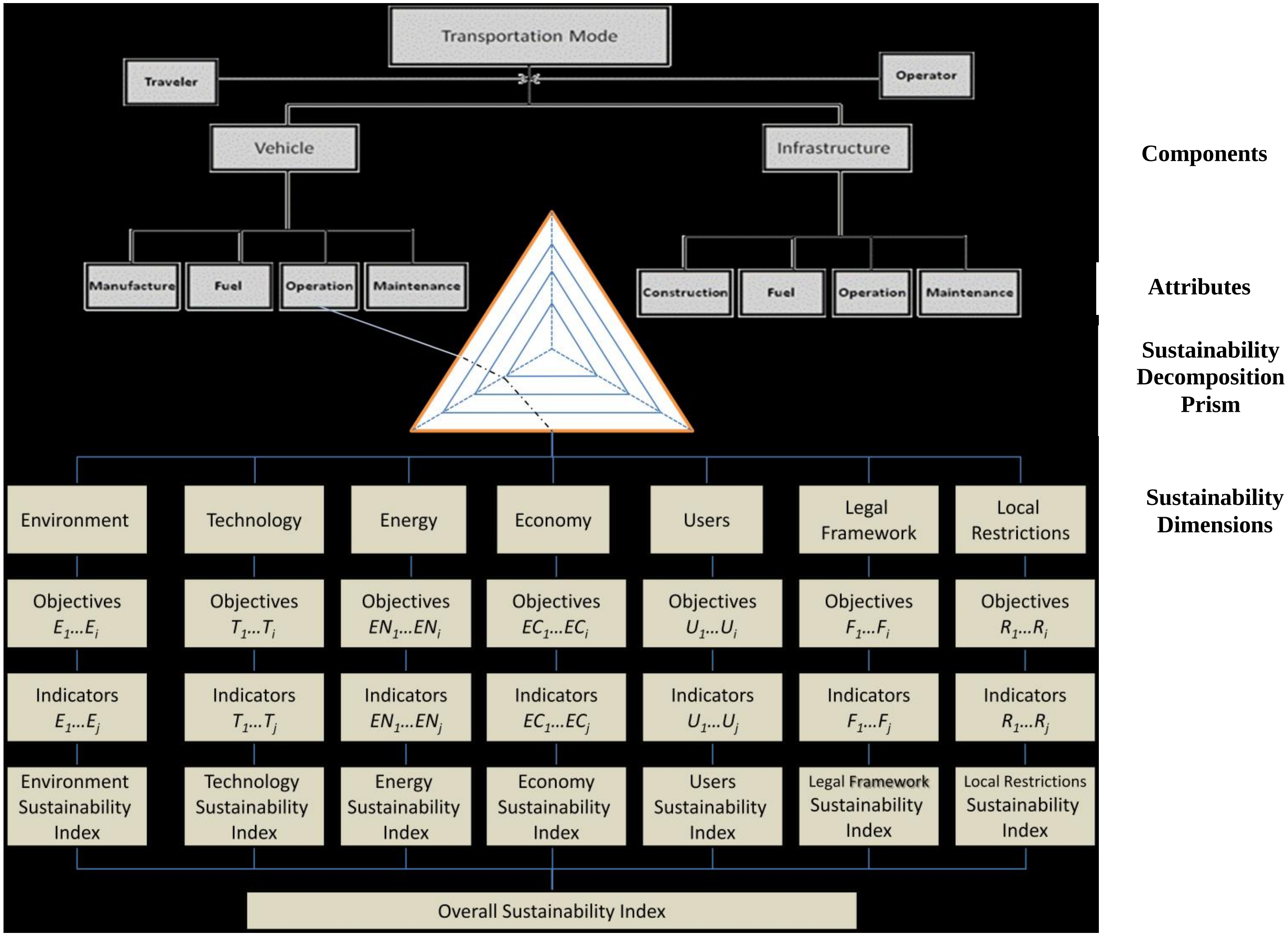

Figure 4.6. Transportation Mode Components, Attributes, and Decomposition into Sustainability Dimensions

4.3. Sustainability Dimensions, Objectives and Indicators

This section presents the sustainability dimensions and the proposed indicators for the LCSF. Sustainability goals express the community's needs; since the proposed sustainability framework is a generic one that can be adapted for application in every community, goals and objectives promote transportation system sustainability.

Indicators are defined as 'selected, targeted, and compressed variables that reflect public concerns and are of use to decision-makers' (Gudmundsson 1999.) Developed indicators for sustainable transportation assessment as it was revealed in the literature review are grouped under four main sustainability dimensions 1) Transportation system performance, 2) Environment, 3) Society, and 4) Economy. These sustainability dimensions are captured by the sustainable transportation goals described in the two fundamental definitions on sustainable transportation provided by the World Commission on Environment and Development (1987) and the European Council of Ministers of Transport (ECMT 2001).

The proposed LCSF is based upon four major sustainability dimensions 1) Transportation system performance, 2) Environment, 3) Society, and 4) Economy. Several performance measures, which are used for evaluating the four sustainability dimensions, have been collected from the literature review and categorized in sustainability dimensions of the LCSF. The collected indicators, which are categorized as (1) Environment; (2) Technology; (3) Energy; (4) Economy, (5) Users and other stakeholders, (6) Legal framework, and (7) Local restrictions, are shown in Table 4.3. The indicators presented in Tables 4.3 to 4.5 are specifically modified to apply to vehicle; the transportation component examined herein. For example, the indicator comfort used in the literature review to assess a transportation system, for the assessment of vehicles is further divided into indicators including passenger space, goods carrying (cargo) space, leg room and seated probability, etc. The objectives that capture the sustainability dimension of the LCSF are also presented. Additionally, indicators such as trip cost, or fuel cost, or trip time that are applicable only to the vehicle operation stage, are generalized to include all possible parameters from a vehicle's life cycle. For example, the indicator cost included purchase, fuel, insurance, registration, taxes and maintenance cost.

Proposed indicators at the minimum try to address objectives by identifying individual vehicle features that contribute towards objective and goal achievement and therefore maximization of sustainability. When the impacts (i.e., positive or negative) of those features to sustainability are aggregated per vehicle population, their value determines objective/goal achievement and the way that the transportation system should move towards sustainability. Although some vehicle indicators are applicable to the component infrastructure, these are not presented in this research because they need to be modified specifically for implementation in infrastructure sustainability assessment.

Table 4.3. Vehicle Sustainability Objectives and Indicators per Sustainability Dimension (Part A)

Sustainability Dimension	Goal	Objective	Indicator	Reference
Environment	Minimize environmental impact	Minimize global warming	Carbon Dioxide - CO_2	Chester and Horvath 2008, FHWA 2002, Jeon, Amekudzi and Guensler 2008
			Methane - CH_4	Chester and Horvath 2008, FHWA 2002
			N_2O	Chester and Horvath 2008, FHWA 2002
			GHG	Chester and Horvath 2008, FHWA 2002
		Minimize air pollution	Volatile Organic Compound - VOC	Chester and Horvath 2008, FHWA 2002, Jeon, Amekudzi and Guensler 2008
			Carbon Monoxide - CO	Chester and Horvath 2008, FHWA 2002, Jeon, Amekudzi and Guensler 2008
			Nitrogen Oxides - NO_x	Chester and Horvath 2008, FHWA 2002, Jeon, Amekudzi and Guensler 2008
			Particle Matter - PM_{10}	Chester and Horvath 2008, FHWA 2002
			Sulphur Oxides - SO_x	Chester and Horvath 2008, FHWA 2002
		Minimize noise	Noise	FHWA 2002, Jeon, Amekudzi and Guensler 2008
		Minimize utilization of non-renewable sources	% Reused, Recycled	Eads 2001, Litman 2011.
		Minimize externalities on living humans and species	Animal health	Jeon, Amekudzi and Guensler 2008
			Site safety	
			Health	

Table 4.4. Vehicle Sustainability Objectives and Indicators per Sustainability Dimension (Part B)

Sustainability Dimension	Goal	Objective	Indicator	Reference
Technology	Maximize technology performance to help people meet their needs	Maximize vehicle lifetime	Vehicle lifetime Upgrade potential	Litman 2009
		Maximize used resources	Capacity	Litman 2009
		Minimize time losses	Fuel frequency Maintenance frequency	Pembina Institute 2001
		Minimize land consumption	Vehicle storage	Miller 2008,Cambridge Systematics 2009, Jeon, Amekudzi and Guensler 2008
		Maximize supply	Supply	EEA 2002
		Maximize mode choices for all users	Feasibility of use by social excluded groups Readiness	Litman 2011, Kirk, et al., 2010
		Maximize vehicle performance	Engine power	EEA 2002
Energy	Minimize energy consumption	Minimize energy consumption	Manufacturing energy Fueling Energy Operation energy Maintenance energy	Chester and Horvath 2008, FHWA 2002
Economy	Maximize and support a vibrant economy	Reduce user cost requirements	Cost	Gilbert, et al. 2003, Jeon, Amekudzi and Guensler 2008
			Property damage	
		Minimize parking requirements	Parking Cost	ITE 1999; Wolfgang, et al. 2001
		Minimize costs for the community	Safety cost	Cambridge Systematics 2009
		Minimize governmental support	Subsidy Tax revenues	EEA 2002, EEA 2002,Pembina Institute 2001
		Promote welfare	Job opportunities	PCT 2011

Table 4.5. Vehicle Sustainability Objectives and Indicators per Sustainability Dimension (Part C)

Sustainability Dimension	Goal	Objective	Indicator	Reference
Users	Maximize users satisfaction	Maximize transportation performance	Mobility	Cambridge Systematics 2009; Jeon, Amekudzi and Guensler 2008
			Demand	Gilbert, et al. 2003
			Delay	ITE 1999; Wolfgang, et al. 2001
			Reliability	Kirk, et al., 2010, Eads 2001
			Safety	ITE 1999; Wolfgang, et al. 2001,Eads 2001, Jeon, Amekudzi and Guensler 2008
			Global availability Reasonable availability	
		Improve accessibility	Equity of access	Eads 2001, Jeon, Amekudzi and Guensler 2008
		Maximize user comfort	Leg room Cargo space Seated Probability Vehicle breakdown Fueling opportunities	Litman 2009, Eads 2001,Cambridge Systematics 2009
Legal Framework	Comply with laws	Comply with existing legislation (international, national, federal, state, local)	Stringent Adaptability Jurisdiction	EPA 2003a
Local restrictions	Comply with local restrictions	Ensure that public actions are sustainable, while incorporating local values and historical and cultural considerations	Cultural restrictions Superstition	EPA 2003a

Proposed indicators for assessing vehicles are presented in Tables 4.6 to 4.12 categorized in sustainability dimensions and life cycle stages. Each table is separated in four columns that represent the four attributes (i.e., manufacture, fuel, operation and maintenance) of vehicle.

Table 4.6. Environment Life Cycle Sustainability Indicators for Vehicle

	1. Environment		
Manufacture	**Fuels**	**Operation**	**Maintenance**
Emissions	Emissions	Emissions	Emissions
Noise	Noise	Noise	Noise
Safety	Safety	Animal health	Safety
% Reused, Recycled		Health	

Table 4.7. Technology Life Cycle Sustainability Indicators for Vehicle

	2. Technology		
Manufacture	**Fuels**	**Operation**	**Maintenance**
Life expectancy	Frequency of fueling	Vehicle storage	Upgrade potential
Capacity		Supply	Frequency
		Feasibility to be used by social excluded groups	
		Readiness	
		Engine power	

Table 4.8. Energy Life Cycle Sustainability Indicators for Vehicle

3. Energy			
Manufacture	**Fuels**	**Operation**	**Maintenance**
% Energy source	% Energy source	% Energy source	% Energy source
Materials	Explore, produce, transfer	Consumption	Materials
Assembly			Assembly

Table 4.9. Economy Life Cycle Sustainability Indicators for Vehicle

4. Economy			
Manufacture	**Fuels**	**Operation**	**Maintenance**
Cost	Cost to produce, secure, transfer	Cost	Cost
Public subsidy	Safety cost	Tax revenues	Public subsidy
Safety cost	Job opportunities	Public subsidy	Safety cost
Job opportunities		Safety cost	Job opportunities
		Job opportunities	
		Property damage	

Table 4.10. Users Life Cycle Sustainability Indicators for Vehicle

5. Users			
Manufacture	**Fuels**	**Operation**	**Maintenance**
		Mobility	
		Demand	
		Vehicle breakdown	
		Safety	
		Equity of access	
		Fueling opportunities	
		Comfort and Convenience	

Table 4. 11. Legal Framework Life Cycle Sustainability Indicators for Vehicles

6. Legal Framework			
Manufacture	**Fuels**	**Operation**	**Maintenance**
Stringent	Stringent	Stringent	Stringent
Adaptability	Adaptability	Adaptability	Adaptability
Jurisdiction	Jurisdiction	Jurisdiction	Jurisdiction

Table 4.12. Local Restrictions Life Cycle Sustainability Indicators for Vehicles

7. Local Restrictions			
Manufacture	**Fuels**	**Operation**	**Maintenance**
	Superstition	Cultural	

Each dimension of the LCSF with the corresponding indicators is presented below.

Environment - Forming the base of the prism, environment is the broadest component. All activities occur within the environment's limits and for society and economy to be healthy, the first prerequisite is a healthy environment. The European Commission defines a healthy environment as "one of the cornerstones of sustainable development…the natural and cultural heritage that defines our common identity and thus its preservation for present and future generations" (EC 2009.)

a. **Emissions** are an outcome of all attributes (manufacture, fueling, operation and maintenance) of component-vehicle; they have a direct impact on the environment. Emissions are divided into two sets of indicators based on the set objectives; greenhouse gases (GHG) and air quality. Specific indicators are developed for each one of the objectives; CO_2, CH_4, N_2O, and total GHGs for greenhouse gas assessment, and VOC, CO, NO_x, PM_{10} and SO_x for air quality assessment.

Emissions are an outcome of all attributes for both components (vehicle manufacture or infrastructure construction, fuels or energy, operation and maintenance); they have a direct impact on the environment. The selection for the emission-indicators is based on their effect on human and environmental health (EPA 2009b):

Carbon Dioxide (CO_2): Creates greenhouse gas which contributes to the global climate change.

Methane (CH_4): is a greenhouse gas that remains in the atmosphere for approximately 9-15 years. Methane is over 20 times more effective in trapping heat in the atmosphere than carbon dioxide (CO2) over a 100-year period.

Nitrous Oxide (N_2O): Nitrous oxide is a major greenhouse gas. Considered over a 100 year period, it has 298 times more impact per unit weight than carbon dioxide.

Sulphur Dioxide (SO_2): Develops respiratory effects, forms acid rains which damages forests and crops, and causes decay of building materials and paints.

Carbon Monoxide (CO): At low concentrations causes fatigue, chest pain in people; at higher concentrations causes impaired vision and coordination, headaches, dizziness, confusion and nausea.

Nitrogen Oxides (NO_x): Causes respiratory disease and contributes to ground-level ozone.

Volatile Organic Compound (VOC): Causes airway irritation, coughing, permanent lung damage with repeated exposures, contributes to creation of ground level ozone which has detrimental effects on plants and ecosystems

Particle Matter of 10 micrometers or less in aerodynamic diameter (PM_{10}): Causes irritatation to people's eyes, nose, throat, and lungs.

b. **Noise** is an outcome of all attributes and it has an impact on human health.

c. **Safety** is referred to the number of fatalities and injuries that occur during maintenance, securing or exploring of fuels, maintenance of vehicles.

d. **Recycled or reused parts** of vehicles and infrastructure refer to the proportion of recycled materials that offset natural resources in manufacturing, construction or maintenance activities.

e. **Health includes** human health problems associated with exposure of humans to emissions.

f. **Animal health** refers to the animal fatalities and injuries due to vehicle manufacturing, construction, fueling and operation

Technology - Technology refers to all components of a system made by humans to meet their needs. Infrastructure is a necessary element for every system to operate; it is part of technology. Infrastructure occupies land area that offsets other land uses; it promotes or hampers the welfare of a community and it connects or separates communities. These are features that are related to environment, economy and society. Globally, technology is one of the most rapidly developing and resource consuming sectors. Manufacturing, fueling, maintaining and operating technology should minimize the consumption of non-renewable energy sources, maximize the reuse and recycling of materials, maintain biodiversity, keep activities within environmental limits, and satisfy the users. Technology satisfies a broad spectrum of human needs including the generation and distribution of energy.

a. **Life expectancy** refers to the expected lifetime of a vehicle. This is fundamental to developing annual measures based on proposed indicators.

b. **Capacity** refers to the maximum number of passengers that each mode can accommodate in the unit of time.

c. **Frequency** of fueling refers to the time required to fuel a vehicle; the higher the time losses, the less satisfied the user is. This criterion is significant for short range modes.

d. **Vehicle storage** when not in use is a fundamental requirement. The space occupied by the vehicle depends on the operational characteristics of the vehicle, such as hours of operation, headway, etc.

e. **Supply** refers to the number of persons that can be moved per hour per vehicle. It is a generalized term for vehicular mode capacity.

f. **Feasibility of use** by special groups including the elderly, children and disabled persons.

g. **Readiness** refers to the status of development of vehicle technology (off-the-shelf, pilot deployments, prototypes, experimental, conceptual.)

h. **Upgrade potential** refers to the flexibility and easiness of the vehicle to be rehabilitated or renovated by following changes in demand and technology.

i. **Maintenance frequency** refers to the number of times a vehicle has to replace parts and fluids and an infrastructure has to be repaired to keep providing a safe service to their users during their life time.

Energy - Energy is a major component that is directly connected with environment and economy. Energy availability, demand, price and actual consumption have short term and long term impacts on lifestyles. Consumption of non-renewable energy sources generates emissions that are harmful to humans in the short term, whereas in the long term, dependence on non-renewable energy sources set activity limitations to a community, thus human needs cannot be met. Technology satisfies a broad spectrum of human needs, and the generation and distribution of energy are part of these needs. Sustainable communities generate energy by using renewable resources or resources that can be replenished at a faster rate than energy is consumed. Overutilizing non-renewable energy sources deprives energy from future generations. The energy aspects are of major interest to the analysis of transportation modes because they require a considerable amount of energy to be built –both for the vehicles and for the infrastructure on which they operate. Additional energy is required for the vehicles to be operated, maintained, refurbished and eventually disposed. All these processes also generate a large amount of pollutants.

a. **Proportion of energy sources** refers to the source of energy used per attribute.
b. **Manufacturing energy** refers to the energy related to the following processes: raw material recovery and extraction, material processing and fabrication, vehicle component production, vehicle assembly and infrastructure construction.
c. **Fueling energy** includes the following processes: primary energy production, transportation, and storage; fuel production, transportation, storage, and distribution.
d. **Operation energy** refers to the energy a vehicle (propulsion) or infrastructure (lighting, elevators, escalators, etc.) needs to operate.
e. **Maintenance energy** refers to the energy required to maintain the vehicle and the corresponding infrastructure over its lifetime and finally dispose it.

Economy – The economy has its foundations on the three layers beneath it. Economic development that did not fall within environmental limits used to be a practice for eons and continues to be applied in several regions. However, global restrictions such as the Kyoto protocol externalized the costs of pollution and energy consumption. The creation of a sustainable economy requires partial utilization of energy and technology and development within environmental limits. An unsustainable economy results in destruction of environment, affects poor social groups disproportionally and leads to social instability and unsustainable communities.

a. **Cost r**efers to the cost of all attributes that can be interpreted in monetary terms.

b. **Public subsidy** refers to the portion covered by taxpayers.

c. **Safety cost** includes the expenses for safety measures, the cost of fatalities and injuries.

d. **Job opportunities** refer to the number of new job positions that will be created.

e. **Property damage** is the cost of vehicle damage.

f. **Tax revenues** refer to the income that is gained when vehicles are in operation through taxation (e.g., fuel taxation.)

Users -Users is a representation of a large set of stakeholders including individuals (e.g., residents or travelers), groups (e.g., schoolchildren), private companies (e.g. taxis, private fleet operators, etc.) and public agencies (e.g. regulatory, operation-and-maintenance agencies, etc.) Depending on the application, users can represent specific social groups. For example, the entire community is the user of electricity from its power plant, but only riders are the users of its bus system. The system's output is the attribute that controls the users' personal choice, as to when, how and at what level (amount) they choose to use this output. Each user perceives the system's output differently, hence the choices often vary. Population displacement for the installation of new or expanded systems is also a form of user costs.

a. **Demand** refers to the number of persons per vehicle per hour that choose to or desire to utilize the subject mode.

b. **Mobility** is the provision of social and economic opportunities by the transportation network. Mobility indicators are the network coverage and average speed of it.

c. **Vehicle breakdown** refers to the vehicle failures during service hours, due to mechanical failure or other reasons.

d. **Equity of access** to the vehicle is measured by the proportion of individuals that use a specific type of vehicle by ethnicity/social group.

e. **Reliability** refers to the ability of a mode to provide a satisfactory and consistent level of service.

f. **Safety** refers to the number of accidents or fatalities that have been recorded with a specific type of vehicle. Safety is a complicated criterion that is affected by the socio-economic characteristics of each community. Comparison of different existing vehicle types in terms of safety can be performed by considering injuries and fatalities. Due to lack of data, safety comparison for different technologies of passenger cars cannot be performed yet. However, within the next years there might be separation of safety performance for alternative fuel vehicles when they are involved in accidents.

Legal framework – Legal framework relates to existing legislation (international, national, federal, state, local) which controls the construction and operation of a system.

For example, particular locations of a community are protected by historical preservation, environmental, coast line management and other laws.

a. **Stringent** refers to whether the existing legal framework is strict or flexible to permit, enforce, or support implementation of new mode(s). For example, in March 2009 the environmental law of Hawaii as interpreted by its courts closed the Hawaii Superferry, a $0.5 billion interisland ferry service that began operations in early 2008 with the governor's approval, but without an environmental assessment.

b. **Adaptability** refers to the degree that the existing legal framework may follow the trends and norms, indicated by the market, in terms of new technologies etc. that affect the modes.

c. **Jurisdiction** refers to the transparency and clarity with which different agencies that are involved in the implementation of a mode, are allocated to their responsibilities, authority and rights.

Local restrictions - Feasibility constraints, cultural heritage and archeological sites may not be represented as explicit restrictions in the legal framework. Local conditions form a set of restrictions for the deployment, upgrade or expansion of a system. This is an area in which large changes may occur over time as technology makes feasibility constraints obsolete (e.g., underwater tunneling), or changes in cultural sensitivity (e.g. some archaeological sites or areas of areas of worship, may be wholly removed and restored elsewhere.)

a. **Cultural restrictions** refer to the cultural heritage that a community preserves, which may restrict the implementation of a mode.

b. **Superstition** refers usually to local beliefs related to utilization of natural energy sources or construction on, under or above sacred grounds.

4.4. Vehicle Technologies

Urban on-road vehicle types and propulsion options examined in this study include internal combustion engine vehicle, hybrid electric vehicle, fuel cell vehicle, electric vehicle, plug-in hybrid vehicle, internal combustion pickup truck, internal combustion SUV, diesel bus, bus rapid transit and car-sharing.

The above framework is applied for the assessment of six light-duty vehicles, a car-sharing program with two different types of vehicles and two transit buses.

Internal Combustion Engine Vehicle (ICEV) is the most frequently used power source for motor vehicles. The power generation is based on the conversion of chemical energy from the fuel into heat through combustion. If the fuel combustion takes place in a cylinder, the process is called internal combustion: The heat energy increases the pressure within a cylinder, the air and fuel mix is ignited by a spark (gasoline) or self ignited due to pressure (diesel), it performs work as it expands and is converted into mechanical work via a reciprocating shaft mechanism. The ICEV used in this dissertation converts gasoline into motion (Bosch 2007.)

Hybrid Electric Vehicle (HEV) combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system. The electric powertrain aims to achieve either better fuel economy or better performance than a conventional vehicle. Modern HEVs utilize efficiency improving technologies such as regenerative braking, to convert the vehicle's kinetic energy into electric energy to charge the battery. The basic components of a HEV are shown in Figure 4.7 (Nice and Layton 2011.)

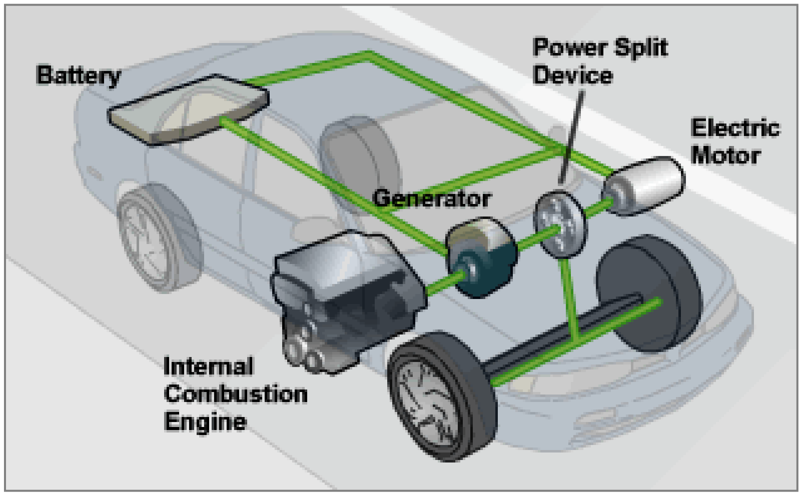

Figure 4.7. Basic Components of a HEV

HEVs can be classified according to the way in which power is supplied to the drivetrain:

i. In parallel hybrids (Figure 4.8), the ICE and the electric motor are both connected to the mechanical transmission and they simultaneously transmit power to drive the wheels, usually through a conventional transmission. Parallel hybrids are also capable of regenerative braking and the ICE can also act as a generator for supplemental recharging (GM 2006.)

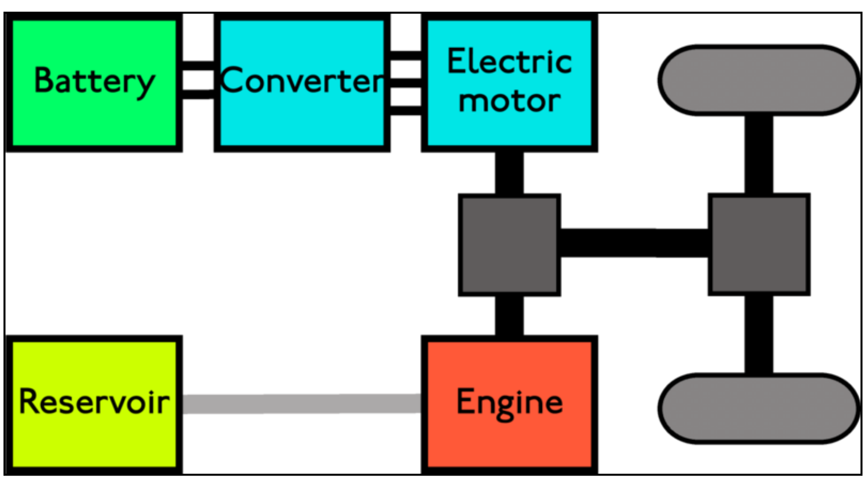

Figure 4.8. Structure of Parallel HEV Components

ii. In series hybrids (Figure 4.9), the electric motor is the only component that drives the drivetrain, and the ICE works as a generator to power the electric motor or to recharge the batteries. The battery pack can also be recharged through regenerative braking. Series hybrids usually have a smaller combustion engine but a larger battery pack as compared to parallel hybrids (GM 2006.)

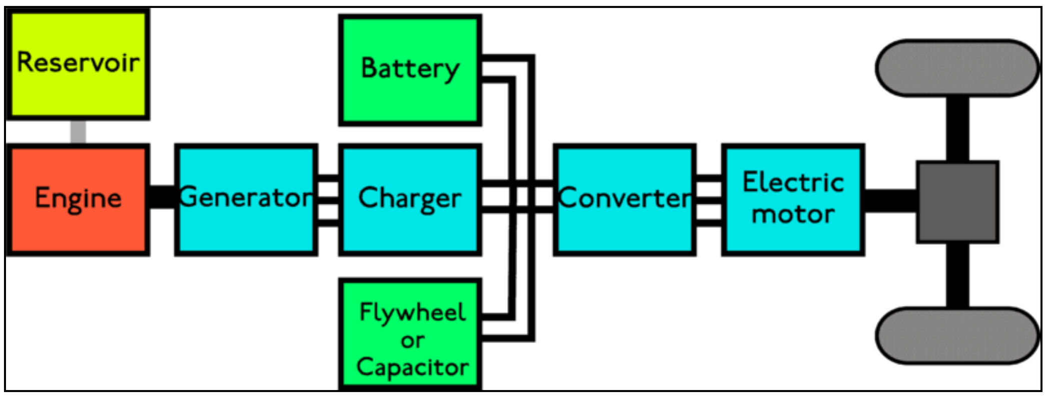

Figure 4.9. Structure of In Series HEV Components

iii. Power-split hybrids have the benefits of a combination of series and parallel characteristics as shown in Figure 4.10. Overall, they are more efficient than other HEV types, because series hybrids tend to be more efficient at lower speeds and parallel tend to be more efficient at high speeds (GM 2006.)

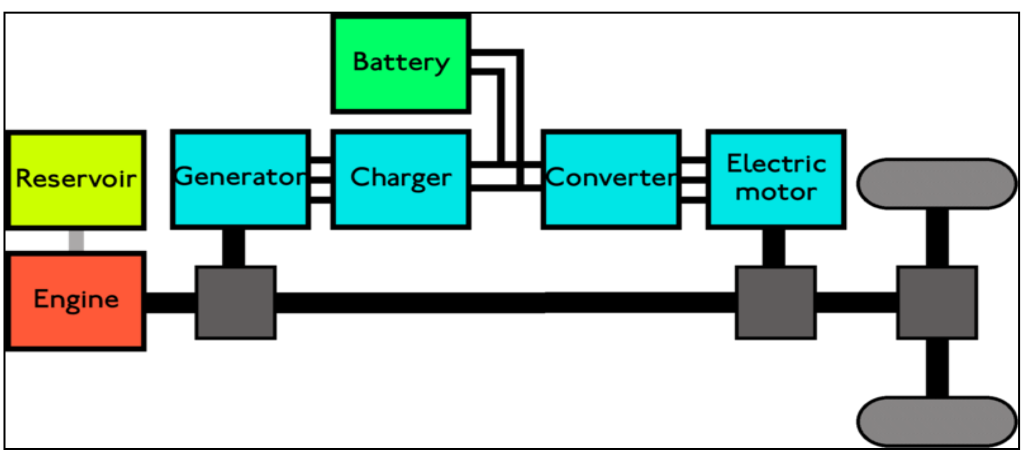

Figure 4.10. Structure of Power-Split HEV Components

Fuel Cell Vehicle (FCV) use a propulsion system that uses hydrogen to produce electricity, powering its on-board electric motor. The major components of a typical FCV are illustrated in Figure 4.11. All fuel cells are made up of three parts: (1) an electrolyte, (2) an anode, and (3) a cathode (EPA 2010.) In principle, a hydrogen fuel cell functions like a battery, producing electricity, which can run an electric motor. A FCV during its operation stage produces mainly water and heat; however, the production of the hydrogen might generate pollutants unless the hydrogen production is based only on renewable energy sources. The fuel cell stack converts hydrogen gas with oxygen from the air into electricity to drive the electric motor that propels the vehicle. Polymer Electrolyte Membrane (PEM) fuel cells are used in automobiles – also called Proton Exchange Membrane fuel cells. Figure 4.12 shows how a PEM fuel cell works. The potential power generated by a fuel cell stack depends on the number and size of the individual fuel cells that comprise the stack and the surface area of the PEM (EPA 2011b.)

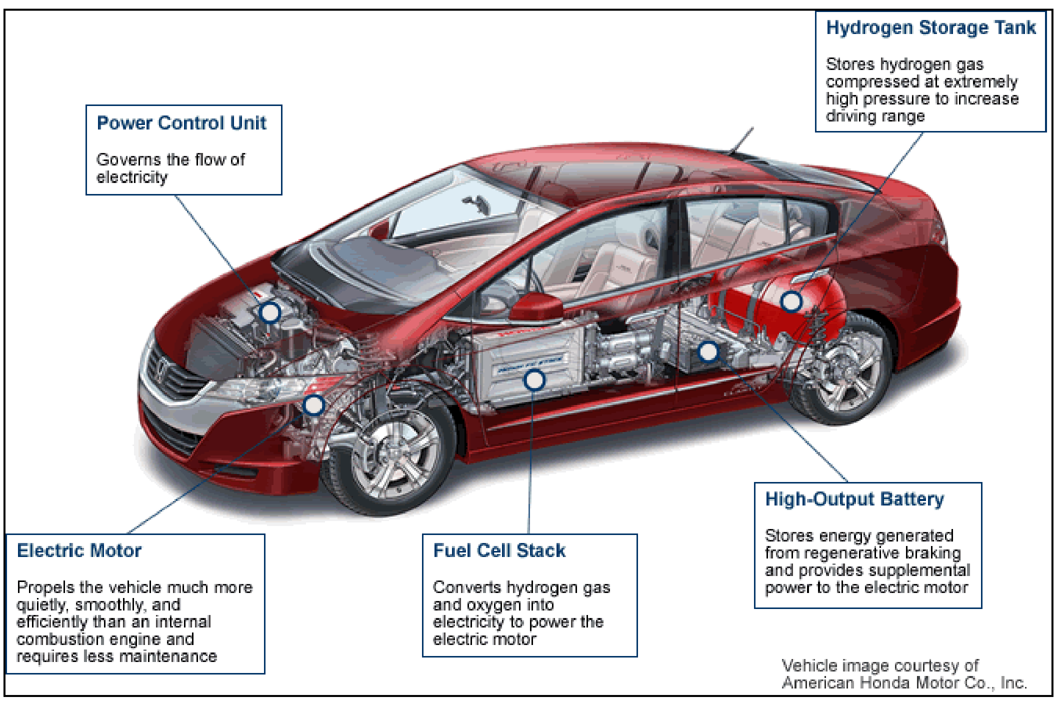

Figure 4.11. Basic FCV Components

These vehicles are in the early stages of development, and several challenges must be overcome before they will be competitive with conventional vehicles.

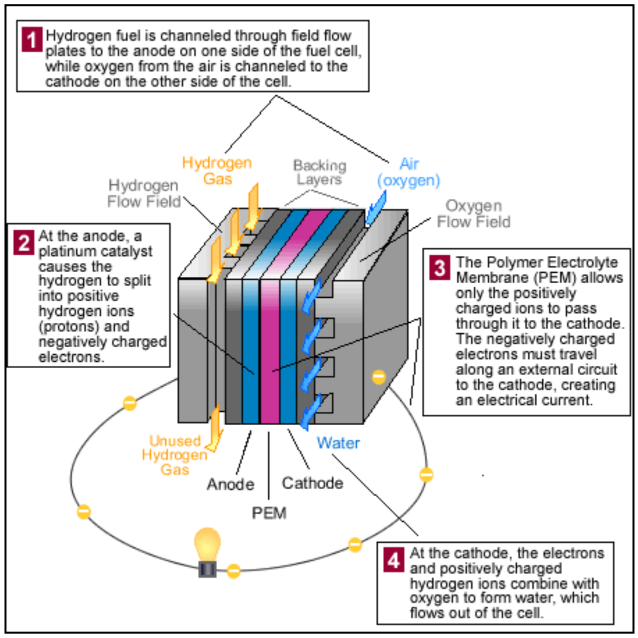

Figure 4.12. Operation of a Polymer Electrolyte Membrane Fuel Cell

Electric Vehicle (EV) refers to a vehicle that is powered entirely by electric energy, stored in a large battery pack which is charged from an external power source. Usually the electric motor acts as a electric generator; it creates energy from vehicle braking, which is then stored in the battery. Based on the type of transmission; the use of a clutch, gearbox, differential, and fixed gearing; and the number of battery packs and motors there are many variations on the EV design. However, a basic EV system is shown in Figure 4.13. The power of a vehicle electric motor, as in other vehicles, is measured in kilowatts (kW.)

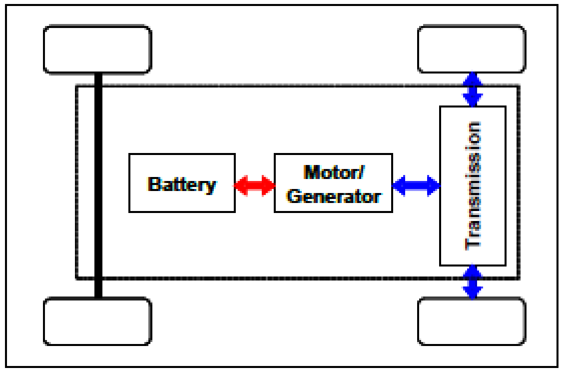

Figure 4.13. Schematic Electric Vehicle Main Components

Plug-in Hybrid Electric Vehicle (PHEV) is a hybrid electric vehicle with rechargeable batteries that can be fully charged by connecting a plug to an external electric power source. A PHEV shares the characteristics of both a HEV, having an electric motor and an ICE; and of an EV, having a plug to connect to the electrical grid. PHEVs eliminate the "range anxiety" associated with EVs, because the combustion engine works as a backup when the batteries are depleted. The Chevrolet Volt is a series plug-in hybrid, although GM prefers to describe the Volt as an electric vehicle equipped with a "range extending" gasoline powered ICE as a generator and therefore dubbed an "Extended Range Electric Vehicle" (Domenick 2009.) For the PHEV, the all-electric range is 40 miles and the total range with a full tank of gasoline 365 miles in this dissertation (Chevrolet 2010.)

Internal Combustion Pickup Truck (ICPT) is a light motor vehicle with an open-top rear cargo area which is almost always separated from the cab to allow for chassis flex when carrying or pulling heavy loads (Duffy 2003.) The ICPT modeled in this study uses gasoline as fuel.

Sports Utility Vehicle (SUV) is a generic marketing term for a vehicle built on a light-truck chassis. Roughly after year 2000 several SUVs were developed on sedan platforms. SUVs are usually equipped with four-wheel drive, with some models having the ability to be used as an off-road vehicle. Not all four-wheel drive vehicles are termed as SUV. Some SUVs include the towing capacity of a pickup truck with the passenger-carrying space of a minivan or large sedan. SUVs can be either classified as ICEV or HEV. For this study a gasoline powered SUV is used.

Car-Sharing (CS) is a service that provides members with access to a fleet of vehicles on an hourly basis. CS operators are usually for profit companies, or they can be non-profit with an environmental mission. Members may book their preferred vehicle online or by phone, and walk to the nearest location to pick it up. They are billed at the end of the month for time and/or mileage. CS in 2004 was accounting for just 0.03% of the U.S. urban population and licensed drivers (TCRP 2005.) CS differs from traditional car rentals in the following ways (Shaheenet al. 2009):

- CS is not limited by office hours.
- Reservation, pickup, and return is all self-service.
- Vehicles can be rented by the minute, by the hour, as well as by the day.
- Users are members and have been pre-approved to drive (background driving checks have been performed and a payment mechanism has been established.)
- Vehicle locations are distributed throughout the service area, and often located for access by public transportation.
- Insurance and fuel costs are included in the rates.

- Vehicles are not serviced (e.g., cleaning, fueling) after each use, although certain programs such as Car2Go continuously clean and fuel their fleet (Shaheenet al. 2009.)

Diesel Bus (DB) a heavy duty motor vehicle designed to carry passengers. The most common type of bus is the single-decker bus, the double-decker buses and the articulated buses. Smaller bus types include minibuses and coaches. Buses may be used for scheduled bus transport, scheduled coach transport, school transport, private hire, tourism; promotional buses may be used for political campaigns and others are privately operated for a wide range of purposes. A diesel engine is a reciprocating-piston engine with internal mixture formation and auto-ignition. It uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion. The diesel engine has the highest thermal efficiency of any regular internal or external combustion engine due to its very high compression ratio (Bosch 2007.)

Bus Rapid Transit (BRT) is a bus based transit system that delivers fast, comfortable, and cost-effective urban mobility through the provision of segregated right-of-way infrastructure, rapid and frequent operations in marketing and customer service. From a customer's perspective, a car-competitive public transportation service is one that competes in terms of total travel time, comfort, cost and convenience. The capacity and speed characteristics of BRT are defining features that set it apart from conventional bus services (ITDP 2007.) Conventional standard (40 ft.) and articulated diesel buses (60 ft.) are used for BRT operations. Innovations in vehicle design include (1) "clean" vehicles (e.g., low-sulfur diesel fuel, diesel-electric hybrids, and possibly fuel cells in the future),

(2) dual-mode (diesel-electric) operations through tunnels, (3) low-floor buses; (4) more doors and wider doors, and (5) use of distinctive, dedicated BRT vehicles (TCRP 2003.)

4.5. LCA Tools

For the quantification of life cycle emission and energy indicators three different LCA tools were used: The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) 1.7 and 2.7 models developed by the Argonne National Laboratory, the MOBILE6.2 model developed by the U.S EPA and the EIO-LCA (Environmental Input-Output Life Cycle Assessment) model developed at Carnegie Mellon University were used for the analysis and quantification of the lifetime energy and emissions related indicators.

GREET provides a comprehensive, lifecycle-based approach to compare the energy use and emissions of conventional and alternative fuel types (e.g., biomass, natural gas, hydrogen, electricity etc.) as well as of conventional and advanced vehicle technologies (e.g., hybrid electric vehicles and fuel cell vehicles). GREET is composed of two parts: a) the fuel-cycle GREET 1.7 model which contains data on fuel cycles and vehicle operations, and b) the vehicle-cycle GREET 2.7 model which estimates the energy and emission effects associated with vehicle manufacturing (material recovery and production, vehicle component fabrication, vehicle assembly), maintenance and disposal/recycling.

The emissions include five indicator pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with diameters of 10 micrometers or less (PM_{10}). The model also calculates the fuel and vehicle cycle emissions of three GHGs (CO_2, CH_4, and N_2O) and the fuel and vehicle cycle consumption of total energy, fossil fuel, and petroleum.

GREET 1.7 enables the well-to-wheel (WTW) analysis of fuel-cycles, for various fuel/vehicle systems. Based on user input, GREET a) conducts simulation studies on energy utilization and emissions associated with production and distribution activities of different transportation fuels (well-to-pump activities), and b) analyzes the energy use and emissions associated with vehicle operation for advanced vehicle technologies (pump-to-wheel activities). GREET 1.7 may simulate more than 100 fuel production pathways and 70 vehicle/fuel systems. The typical simulation steps with GREET 1.7 are shown in Figure 4.14 (Wang et al 2007.)

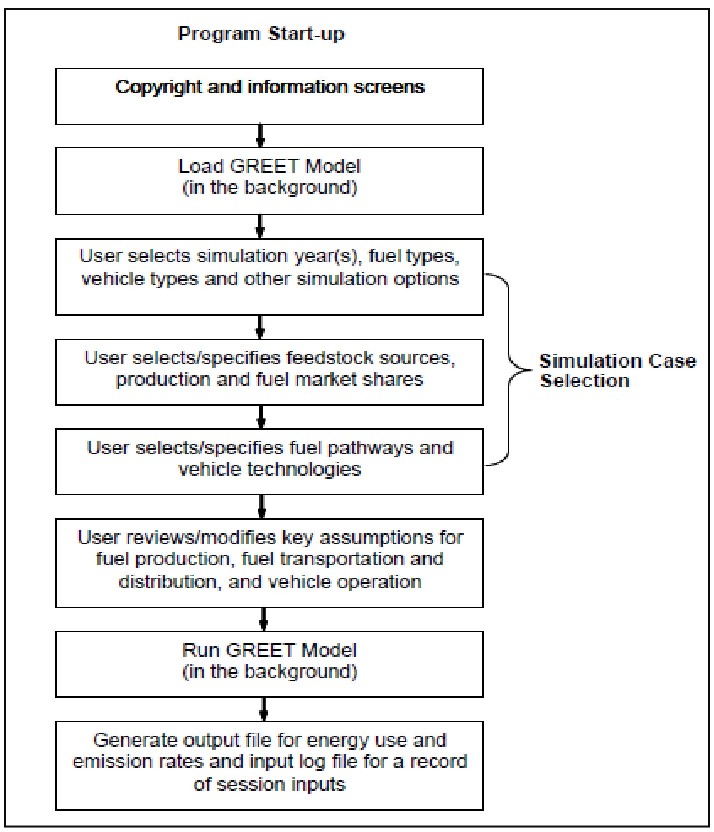

Figure 4.14. Interactive Phases in a Typical GREET Session

GREET 2.7 calculates the energy use and emissions that are required for vehicle component production; battery production; fluid production and use; and vehicle assembly, disposal, and recycling. GREET 2.7 is based on a mid-size passenger car platform. Figure 4.15 (Burnham et al. 2006) shows the simulation logic behind GREET 2.7 and its interaction with GREET 1.7.

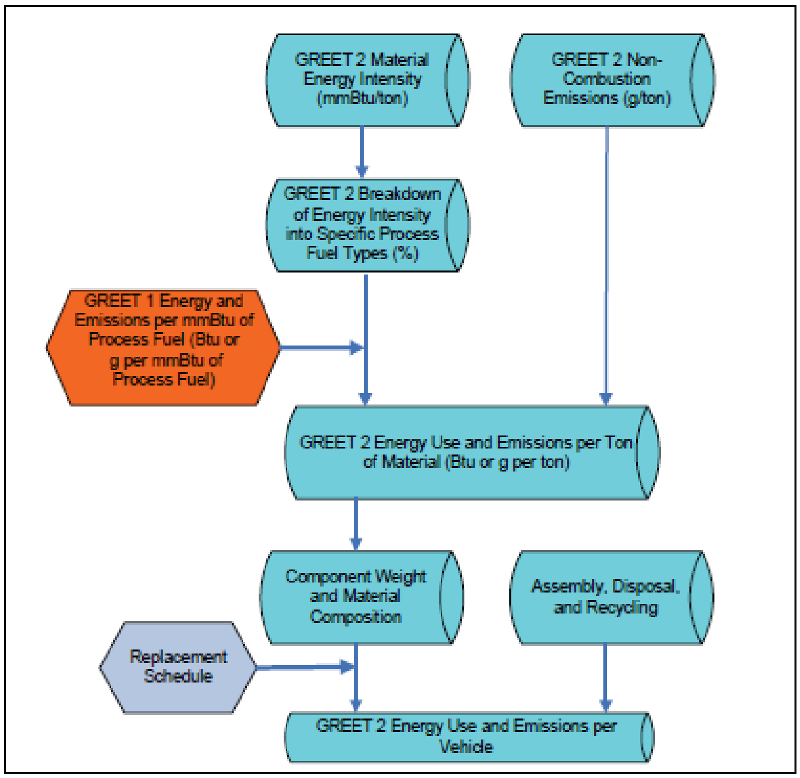

Figure 4.15. Simulation Logic for GREET Vehicle Cycle Analysis

In GREET 2.7 each vehicle system is decomposed into subsystems and the subsystems are decomposed into parts. There are eight major vehicle systems which are not applicable to every car due to technology differences as shown in Table 4.6 (Burnham et al. 2006):

- Body
- Powertrain

- Transmission
- Chassis, electric traction motor
- Generator
- Electronic controller
- Fuel cell auxiliaries

Appendix A provides definitions for the major parts and subsystems in each component category (i.e., body, powertrain, transmission, chassis, electric-drive, battery, and fluid). The total weight of each vehicle is broken down into three major categories: a) vehicle components, b) battery, and c) fluids.

Table 4.13. Vehicle Systems per Vehicle Type Included in GREET 2.7

System	ICEV	HEV	FCV
Body system	✓	✓	✓
Powertrain system	✓	✓	✓
Transmission system	✓	✓	✓
Chassis system	✓	✓	✓
Traction motor		✓	✓
Generator		✓	
Electronic controller		✓	✓
Fuel cell auxiliary system			✓
Batteries	✓	✓	✓
Fluids (excluding fuel)	✓	✓	✓

MOBILE was a model designed by the U.S. EPA to estimate emission factors for gasoline and diesel highway motor vehicles. It is being replaced by MOVES (Motor Vehicle Emission Simulator), a new emission modeling system (EPA 2011c.) Written in Fortran the model calculates emission rates under various conditions affecting in-use emission levels (e.g., ambient temperatures, average traffic speeds) as specified by the modeler. MOBILE models have been used by EPA to evaluate highway mobile source control strategies; by states and local and regional planning agencies to develop emission inventories and control strategies for State Implementation Plans under the Clean Air Act; by metropolitan planning organizations and state transportation departments for transportation planning and conformity analysis; by academic and industry investigators conducting research; and in developing environmental impact statements. MOBILE6.2 calculates average in-use fleet emission factors for:

- Three criteria pollutants: hydrocarbons (HC); carbon monoxide (CO); and oxides of nitrogen (NO_x). Exhaust particulate matter (which consists of several components), tire wear particulate matter, brake wear particulate matter, sulfur dioxide (SO_2), ammonia (NH_3), six hazardous air pollutants, and CO_2
- Twenty eight different vehicle classes including gas, diesel, natural-gas-fueled cars, trucks, buses, and motorcycles
- Calendar years between 1952 and 2050

Input parameters for MOBILE6.2 are:

- Calendar year
- Month (January, July)
- Hourly Temperature
- Altitude (high, low)
- Weekend/weekday
- Fuel characteristics (Reid vapor pressure, sulfur content, oxygenate content, etc.)
- Humidity and solar load
- Registration (age) distribution by vehicle class

- Annual mileage accumulation by vehicle class
- Diesel sales fractions by vehicle class and model year
- Average speed distribution by hour and roadway
- Distribution of vehicle miles traveled by roadway type
- Engine starts per day by vehicle class and distribution by hour
- Engine start soak time distribution by hour
- Trip end distribution by hour
- Average trip length distribution
- Hot soak duration
- Distribution of vehicle miles traveled by vehicle class
- Full, partial, and multiple diurnal distribution by hour
- Inspection and maintenance (I/M) program description
- Anti-tampering inspection program description
- Stage II refueling emissions inspection program description
- Natural gas vehicle fractions
- HC species output
- Particle size cutoff
- Emission factors for PM and HAPs
- Output format specifications and selections

EIO-LCA estimates the energy resources and the emissions resulting from activities in our economy. EIO-LCA was conceptualized and developed by economist Wassily Leontief in the 1970s, and researchers at Carnegie Mellon University operationalized Leontief's method in the mid-1990s. EIO-LCA provides results on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. Thus, the effect of producing an automobile would include not only the impacts at the final assembly facility, but also the impact from mining metal ores, making electronic parts, forming windows, etc. that are needed for parts to build the car.

It is one technique for performing a life cycle assessment, an evaluation of the environmental impacts of a product or process over its entire life cycle. The method uses information about industry transactions – purchases of materials by one industry from other industries, and the information about direct environmental emissions of industries, to estimate the total emissions throughout the supply chain. EIO-LCA is a linear model. The results represent impacts through the production of output by the sector with increased demand. For the most part then, the use phase and end-of-life phases are not directly included in the results. However, additional analyses using EIO-LCA can model these life cycle stages. EIO-LCA has been used in many studies by researchers, LCA practitioners, business users, students, and others. The application of EIO-LCA contains an uncertainty that is mostly related to:

- Old data
- Uncertainty inherent in original data
- Incomplete original data
- Aggregated original data
- Aggregation of sectors

The application of the LCSA for the assessment of urban transportation modes, and the assumptions for the quantification of sustainability indicators are presented in

Chapter 5. The LCSF is applied in the assessment of road-vehicles to further assess urban transportation sustainability of three metropolitan areas; however its application can be expanded to other systems and demographic areas.

CHAPTER 5

DATA SOURCES, MODELING ASSUMPTIONS, AND ANALYSIS

Eleven vehicles are analyzed and their sustainability performance is compared using the LCSF and the indicators that were presented in Chapter 4. The data used and the modeling assumptions that were made provide a generic life cycle sustainability model. The model can be modified based on regional or local data input.

The objective of this chapter is to present the process of sustainability indicator quantification by presenting the data sources, the modeling assumptions, final sustainability assessment results and the creation of an overall sustainability index that can be used to compare vehicle sustainability performance. The first section of this chapter presents the defined objectives and performance measures that address the different goals grouped for each sustainability dimension. Then the urban vehicle models assessed in this dissertation are presented together with their basic characteristics. The next four sections provide a comprehensive quantification of sustainability indicators for each sustainability dimension. The first of those sections includes both environmental and energy sustainability indicators due to the modeling process that was followed. In that section emissions and energy related indicators are quantified for all life cycle stages of urban vehicles. The last section of this chapter presents the developed sustainability dimension indices and overall sustainability index per vehicle to facilitate comparison between different modes and incorporation of sustainability into transportation planning. Additionally, the attainment sustainability ratio is developed for each vehicle to supplement and support decision making process.

5.1. Life Cycle Sustainability Assessment

The LCSA uses the theory and methodology presented in previous chapters to quantify a set of sustainability indicators and to provide life cycle comparisons between urban transportation modes. This study considers the sustainability dimensions that were presented in Chapter 4 and quantifies a set of sustainability indicators which are the basis for the assessment of urban transportation vehicles. The identified goals address issues related to environmental, technological, energy, economic and users' aspects of transportation planning. Tables 5.1 to 5.3 present the sustainability dimensions with the corresponding defined goals, objectives and indicators. Tables 5.1 to 5.3 present the sustainability indicators that are quantified in this study. Sustainability indicators in hatched cells are proposed for application to specific projects, and are not quantified herein.

Indicators that assess the effectiveness of a transportation system (network or part of the network) are considered as the fundamental indicators for transportation sustainability planning. In this assessment of urban transportation vehicles, in addition to the system performance indicators, the indicators that are related to environment, technology, energy, economy and users are considered. Safety is excluded from the quantification process for the following reasons:

- Safety is a complex indicator that greatly differs across different socio-demographic characteristics.
- There are no available recorded accident data that are disaggregated per vehicle technology and vehicle type.

Safety studies have looked into different car and light truck categories, classed according to size and weight of the vehicle but not according to different technologies, such as alternative fuel vehicles, described in this dissertation (Wenzel and Ross, 2002.)

Due to the variable character of the proposed indicators, data for each mode are found from different sources. For example, a recent study on the environmental assessment of passenger transportation (Chester and Horvath 2009) used specific sample vehicles, such as a sedan vehicle, a pickup truck and a SUV, and rail systems, and then it aggregated pollutants per vehicle for different stages of life cycle in order to present the effect of a specific pollutant of a specific vehicle on the environment. Their comprehensive assessment produced GHG emission estimates for rail systems than are far more realistic (higher) that those often proclaimed. The LCSF goes much further than this by offering a detailed assessment along seven dimensions.

Table 5.1. Selected Vehicle Sustainability Indicators (Part A)

Sustainability Dimension	Goal	Objective	Indicator
Environment*	Minimize environmental impact	Minimize global warming	Carbon Dioxide - CO_2 Methane - CH_4 N_2O GHG
		Minimize air pollution	Volatile Organic Compound - VOC Carbon Monoxide - CO Nitrogen Oxides - NO_x Particle Matter - PM_{10} Sulphur Oxides - SO_x
		Minimize noise	Noise
		Minimize externalities on living humans and species	Health

Note (*):Environment and Energy indicators are not fixed but depend on project specific or regional inputs of vehicle average lifetime, annual miles traveled, weight and speed.

Table 5.2. Selected Vehicle Sustainability Indicators (Part B)

Sustainability Dimension	Goal	Objective	Indicator
Technology	Maximize technology performance to help people meet their needs	Maximize vehicle lifetime	Vehicle lifetime Upgrade potential
		Maximize used resources	Capacity
		Minimize time losses	Fuel frequency Maintenance frequency
		Minimize land consumption	Vehicle storage
		Maximize supply	Supply
		Maximize mode choices for all users	Feasibility of use by social excluded groups Readiness
		Maximize vehicle performance	Engine power
Energy *	Minimize energy consumption	Minimize energy consumption	Manufacturing energy Fueling energy Operation energy Maintenance energy
Economy	Maximize and support a vibrant economy	Reduce user cost requirements	Cost Property damage
		Minimize parking requirements	Parking Cost
		Minimize costs for the community	Safety cost
		Minimize governmental support	Subsidy
		Promote welfare	Job opportunities

Note (*):See Table 5.1

Table 5.3. Selected Vehicle Sustainability Indicators (Part C)

Sustainability Dimension	Goal	Objective	Indicator
Users	Maximize users satisfaction	Maximize transportation performance	Mobility Demand Global availability Reasonable availability Delay Reliability Safety
		Improve accessibility	Equity of access
		Maximize user comfort	Leg room Cargo space Seated Probability Fueling opportunities
Legal Framework	Comply with laws	Comply with existing legislation (international, national, federal, state, local)	Stringent Adaptability Jurisdiction
Local restrictions	Comply with local restrictions	Ensure that public actions are sustainable, while incorporating local values and historical and cultural considerations	Cultural restrictions Superstition

In the analysis that follows, all vehicles are assumed to use the same infrastructure (roads), so the indicators that are used herein focus on the component vehicle, and five sustainability dimensions, including Environment, Technology, Energy, Economy and Users. The remaining two dimensions (legal framework and local restrictions) are imposed by communities and they are applicable only to the deployment of specific transportation projects. The set of urban transportation vehicles assessed in this research, their characteristics and the assumptions considered in the modeling are presented in the following section.

5.2. Urban Transportation Vehicles

Based on the sustainability dimensions presented in Chapter 4 a complete set of indicators are developed and quantified to compare the life cycle sustainability performance of urban transportation vehicles. The list of eleven vehicle types examined is as follows:

1. Internal Combustion Engine Vehicle or **ICEV** (2010 Toyota Camry LE)
2. Hybrid Electric Vehicle or **HEV** (2010 Toyota Prius III)
3. Fuel Cell Vehicle or **FCV** (2009 Honda Clarity FCX)
4. Electric Vehicle or **EV** (2011 Nissan Leaf)
5. Plug-In Hybrid Vehicle or **PHEV** (2011 Chevrolet Volt)
6. Gasoline Pickup Truck or **GPT** (2010 Ford F-150 base)
7. Gasoline Sports Utility Vehicle or **GSUV** (2010 Ford Explorer Base)
8. Diesel Bus or **DB** (New Flyer 40′ Restyled)
9. Bus Rapid Transit or **BRT** (New Flyer 60′ Advanced Style BRT)
10. Car-sharing or **CS** program with ICEV (2010 Toyota Camry LE)
11. Car-sharing or **CS** program with HEV (2010 Toyota Prius III)

The analysis focuses on light-duty vehicles (LDV) as these modes account for approximately 85% of daily trips in the U.S. (BTS 2002), two public transit buses and a CS program. The selected sustainability indicators are used to assess different vehicle types and fuels. Simulation of fuel pathways and vehicle types is made for the year 2010. The most representative vehicles for each vehicle type are presented in Table 5.4 to Table

5.7, were selected. These were necessary for extracting impacts based on specific vehicle characteristics.

Table 5.4. Sedan Sales by Model (2010)

	Model	Sales
1	Toyota Camry	313,212
2	Honda Accord	282,530
3	Honda Civic	252,882
4	Toyota Corolla	247,032
5	Nissan Altima	222,553
6	Honda CR-V	203,714
7	Ford Fusion	198,403
8	Chevrolet Malibu	198,365

Table 5.5. HEV Sales by Model

	Vehicle	2006	2007	2008	2009	2010
1	Toyota Prius	106,971	181,221	158,574	139,682	140,928
2	Honda Insight	722	0	0	20,572	20,962
3	Ford Fusion				15,554	20,816
4	Lexus RX400h	20,161	17,291	15,200	14,464	15,119
5	Toyota Camry	31,341	54,477	46,272	22,887	14,587
6	Ford Escape	20,149	21,386	17,173	14,787	11,182
7	Lexus HS 250h				6,699	10,663
8	Toyota Highlander	31,485	22,052	19,441	11,086	7,456
9	Honda Civic	31,251	32,575	31,297	15,119	7,336
10	Nissan Altima		8,388	8,819	9,357	6,710

Table 5.6. Pickup Truck Sales by model (2010)

	Model	Sales
1	Ford F-Series	528,349
2	Chevrolet Silverado	370,135
3	Dodge Ram	199,652
4	GMC Sierra	129,794
5	Toyota Tacoma	106,198
6	Toyota Tundra	93,309
7	Ford Ranger	55,364
8	Nissan Frontier	40,427
9	Chevrolet Colorado	24,427
10	Nissan Titan	23,416

Table 5.7. Top U.S. SUV Registrations (2009)

	Model	Sales
1	Ford Explorer	4,333,795
2	Jeep Grand Cherokee	2,953,706
3	Chevrolet Suburban	2,040,373
4	Chevrolet Tahoe	1,919,180
5	Ford Expedition	1,811,792
6	Chevrolet Blazer	1,585,101
7	Toyota 4Runner	1,524,614
8	Chevrolet Traiblazer	1,442,482
9	Jeep Wrangler	1,345,524
10	Jeep Cherokee	1,340,053

For existing vehicle technologies, such as the ICEV, the HEV and the GPT the three top selling models were used in our analysis, Toyota Camry, Toyota Prius, Ford F-150, respectively. For GSUV the most representative model according to registrations is the Ford Explorer. SUV sales over the last two years have changed significantly due to fluctuations of crude oil prices (Edmunds 2011, AFDC 2011, Pickup Trucks 2011, SEMA 2009). For the FCV, EV, and the PHEV the Honda Clarity, the Nissan Leaf, and the Chevrolet Volt were selected as the most representative of their type. For transit buses a New Flyer 40 ft. restyled bus and a New Flyer 60 ft. advanced style bus was used as representative of the DB and the BRT, respectively. The 40-ft. bus (ranging between 37’6” and 42’5”) is the most prevalent bus size in U.S. transit agencies based on the number of buses built and number of orders per year (FTA 2006.) Diesel fuel has been the most common type of fuel for transit buses. Diesel continues to dominate the bus fuel market, as it accounts for almost 85% of the power sources for the 60,526 buses documented in 2005 (FTA 2006.) Compressed natural gas (CNG), the second most popular power source, accounted for 16.8% of buses newly-built in 2004 and 16.5% of buses on order. Since 2002, California transit agencies choosing the diesel approach have been required to use Ultra Low Sulfur Diesel (ULSD) (FTA 2006.)

For the CS program an ICEV (Toyota Camry) and a HEV (Toyota Prius) were used as these are the dominant types of vehicles in existing CS stations (Zipcar 2011.) The study does not intend to compare specific vehicle models, but instead use the stated vehicles as class representatives for their characteristics (weight, battery, fuel efficiency etc.) For each of the selected vehicle types the assumptions made are shown in Table 5.8.

The average fuel efficiency for each vehicle was calculated based on U.S. urban driving conditions. The vehicle weight in Table 5.7 refers to the curb vehicle weight. Data for each passenger vehicle was extracted from the official website of each vehicle model (Toyota 2010, Nissan 2010, Honda 2010, Ford 2010, Chevrolet 2010 and NewFlyer 2010.)

Table 5.8. Vehicle Characteristics

		ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Weight	*lbs*	3,307	3,042	3,582	3,500	3,781	5,319	4,509	26,000	49,000	3,307	3,042
Average occupancy	*passengers*	1.15	1.15	1.15	1.15	1.15	1.10	1.40	10.50	23.90	4.58	4.58
Average lifetime	*years*	10.6	10.6	15.0	15.0	15.0	9.6	9.6	12.0	12.0	2.0	2.0
Average Annual miles	*miles*	11,300	11,300	11,300	11,300	11,300	11,300	11,300	41,667	41,667	18,000	18,000
Lifetime miles	*miles*	119,780	119,780	169,500	169,500	169,500	108,480	108,480	500,000	500,000	36,000	36,000
Cost to buy (MSRP)	*$ US dollars*	$22,225	$23,050	$48,850	$32,780	$40,000	$22,060	$28,190	$319,709	$550,000	$22,225	$23,050
Fuel Price (Jan. 2010 - W.Coast)	*$ per U.S. gallon*	$2.85	$2.85	$4.90*	$0.16**	$2.85	$2.85	$2.85	$2.94	$2.94	$2.85	$2.85

Note: (*) per kg, (**) per kWh

The average lifetime for the passenger cars and the pickup truck are 10.6 and 9.6 years, respectively (Davis et al. 2011.) Although the average lifetime of new vehicle technologies (e.g., EVs, FCVs) has not been established yet, it is assumed to be the same with the vehicle's battery lifetime which reflects FreedomCAR Program Research and Development goals of a 15 year lifetime (Burnham et al. 2006.) Additionally, after this age a vehicle requires significant maintenance in its interior and exterior parts to keep operating properly and provide adequate safety and comfort to its passengers. Average lifetime for the rest of the vehicles shown in Table 5.8 is taken from literature sources (Davis et al. 2011.) The average bus lifetime is assumed to be 12 years (FTA 2006.) The CS companies tend to take rental vehicles out of service after one or two years in service, thus for this dissertation it is assumed that the average lifetime for a vehicle in a CS program is two years (Car Buying Tips 2010.) After that time the vehicle is assumed to be in operation for 8.6 years, which is the difference between passenger car's lifetime and its years in CS service.

The average vehicle miles traveled (VMT) are assumed to be 11,300 for all light-duty vehicles (Davis et al. 2011.) Based on this assumption, AFVs (FCV, EV and PHEV) replace gasoline vehicles and they will be used in a similar way that gasoline vehicles are being used (commuting and errands,) and not complementary to them. This assumption may be true only for higher income households. The bus mileage complies with the FTA bus specifications that states that providing a 12year/500,000 mile service life is a design requirement specified for all U.S. transit buses. Bus manufacturers must build their buses to meet or exceed this specification (FTA 2006.) For CS programs, based on the shared use vehicle survey, the majority of vehicles are driven for 18,000 miles per year (TCRP 2005.)

The manufacturer's suggested retail price (MSRP) refers to the recommended price that a vehicle should be sold. Prices for the passenger vehicles and buses are given in Table 5.8 (Edmunds 2010, FTA 2007, TCRP 2002.)

The national average vehicle occupancy for a sedan, pickup truck and an SUV, for all areas, is 1.59, 1.49 and 1.92 respectively based on (Davis et al. 2010.) These occupancy rates were adjusted to reflect vehicle occupancy in urban environments. The ratios of the sedan, pickup truck and the SUV relative to the average occupancy ratio of all three vehicle types are 0.952, 0.892, and 1.149 respectively. These ratios were applied to the average occupancy ratio for metropolitan areas; this was estimated to be 1.22 (Commuting in America 2006.) The estimated occupancy ratios are 1.15, 1.10 and 1.40 for sedans, pickup truck and SUV, respectively. The average occupancies for the DB and the BRT are 10.5 and 23.9 respectively (FHWA 2004.) There is no systematic data reporting of the average occupancy of BRT systems. Therefore it was assumed that the occupancy ratio is equivalent to that of an average light-rail transit (LRT), because BRT systems often are designed to perform like LRT (Vincent and Jerram 2006.) The occupancy for a vehicle in a CS program is assumed to be 4.58 based on the estimation that a CS vehicle reduces the need for 4 to 10 privately owned vehicles (Rydén and Morin, 2005.) The lower threshold is considered here.

The price of the gasoline, diesel, electricity and hydrogen as of January 2010 for the West Coast of U.S. was \$2.85/gallon, \$2.94/gallon, \$0.16/kWh and \$4.99/kg respectively (EIA 2010a, EIA 2010b, DOE 2010.)

The presented vehicle characteristics and assumptions form the basis for the quantification of sustainability indicators. The following section presents first the modeling process for emissions (environmental dimension) and energy (energy dimension) for all considered vehicles for each life stage.

5.3. Environmental and Energy Sustainability Indicators

The analysis and quantification of vehicle life cycle energy and emissions related indicators were conducted with the GREET 1.7 and 2.7 models developed by Argonne, MOBILE6.2 model developed by the U.S EPA, and the EIO-LCA model developed at the Carnegie-Mellon University.

Emissions generation and energy requirements are applicable to all attributes of a transportation system (manufacture, fueling, operation and maintenance) of the vehicle; they have a direct impact on the environment and energy consumption. Emissions are divided into two groups based on the set objectives; GHGs and air quality. Specific indicators are developed for each one of the emissions groups; $CO_{2,}$ CH_4, N_2O, and total GHGs for GHG assessment, and VOC, CO, NO_x, PM_{10} and SO_x for air quality assessment.

This section is divided into subsections with each one describing the life cycle tools applied for the quantification of emissions and energy indicators for each vehicle life stage (manufacture, fuel, operation and maintenance), as well as assumptions considered and final results.

5.3.1. Manufacture

GREET 2.7 and EIO-LCA were used to estimate emissions and energy inventory for LDVs and buses (DB and BRT), respectively. Manufacturing energy and emissions in

GREET 2.7 refer to the following basic processes: vehicle materials, batteries, fluids and vehicle assembly. Each of these basic processes is further separated into the following sub-processes.

Vehicle material cycle

- Raw material recovery
- Raw material transportation and processing
- Material production, fabrication and processing.

Battery cycle

- Material production
- Fabrication for the start up
- Storage batteries

Fluid cycle

- Production
- Disposal of coolants
- Engine oil
- Windshield fluid
- Steering fluid
- Brake fluid
- Transmission fluid

Currently, GREET 2.7 does not include energy use and emissions from transportation of raw and processed materials for each process step. However, future versions of the model will likely address this issue because the location of each process step is important in determining air pollution impacts. Transportation of materials is a significant component in the LCA of vehicles as material production can take place outside of the United States. The data requirements for GREET 2.7 focus on vehicle and material components. The vehicle input data includes:

- Vehicle type (i.e., passenger car or SUV)
- Tire replacements per lifetime
- Battery type per vehicle type (i.e., lead acid, Ni-LH or Li-Ion)
- Battery specific power (in W/kg or W/lb)
- Fluids replacements during lifetime of vehicle
- Energy use of battery assembly (mmBtu per ton of battery). This value is a GREET default key assumption and it is derived from Ni-MH and Li-Ion battery assembly data based on the assumption that Ni-MH and Li-Ion assembly require 20% higher energy use than lead-acid battery.

The material input data refers to all materials used for the vehicle components, including vehicle parts, battery and tires. Material data include:

- Material composition for each vehicle component
- Material composition of tires is assumed to be 66.7% plastic and 33.3% steel.
- Battery material composition. GREET default values are considered as input data and are shown in Appendix B
- Share of virgin and recycled materials used in vehicle (Table 5.8)

Intermediate material requirements for final material production can be found in Appendix B. Specific input assumptions related to each vehicle and its components are extracted from the official website of each vehicle mode. These data include:

- Vehicle weight
- Battery weight
- Fluid weight
- Fuel cell stack size (applicable only to FCV)
- Battery size in peak battery power (not applicable to ICEVs)
- Lifetime vehicle miles traveled (VMT)
- Material composition for each passenger car component (percentage per weight)

The weight and battery properties of each vehicle were used as an input data in the model together with GREET's material percentage composition of each vehicle component (body, powertrain, chassis, transmission, generator, etc.)

GREET provides default values for material compositions for three vehicles types, including ICEV, HEV and FCV. In an attempt to obtain more accurate material compositions, a one page questionnaire was developed and distributed first by email and then by mail to the design centers of automobile companies to enquire their input related to vehicle components. The questionnaire asked each company to provide information for selected vehicle models. The questionnaire could not be filled by the companies as we were informed that it is against the policy of each company to provide to public data related to their products especially when these are not available yet to the public. A sample of the questionnaire for each vehicle technology can be found in Appendix C.

Additional material assumptions were made for the EV and PHEV vehicles. The material compositions of the PHEV's components were modeled assuming an 80/20 mix of HEV and ICEV materials, respectively. The percentages of material compositions for the EV components were calculated using the mass of each material for an EV, as these were estimated for electric compact vehicles by ANL (CTR 1998.)

No tire replacements were assumed for all types of vehicles over their lifetime in GREET 2.7, to avoid double counting, as tire replacement is included in the vehicle maintenance stage. Additionally, two battery replacements were considered for the ICEV, the GSUV and the GPT, one for HEV and PHEV and none for the FCV and the EV to reflect FreedomCAR Program R&D goals of a 15-year lifetime, as assumed by ANL (Burnham et al. 2006.)

The energy use of materials that are recycled and later used in a vehicle is taken into account in GREET 2.7 for each specific material. The share of used virgin and recycled materials in vehicle manufacturing is shown in Table 5.9. In order to estimate the amount of energy used during vehicle production, GREET 2.7 developers first had to identify the materials used in the vehicles and then characterize the production processes and, if possible, the recycling processes for each material. Recycling is handled separately for each material. Energy use data for recycling especially for newer and less-common materials may be available only from experimental results or theoretical calculations. For metals recycling is generally less polluting and less energy intensive because the basic material only needs to be remelted. Automotive glass is not currently recycled, but it ends up in the auto shredder residue (ASR.) Energy requirements for individual material production can be found in Appendix D.

Table 5.9. Virgin and Recycled Material Shares for Vehicles

	Virgin Material	Recycled Material
Steel	30%	70%
Wrought Aluminum	89%	11%
Cast Aluminum	41%	59%
Lead	27%	73%
Nickel	56%	44%

The energy and emissions impacts from the manufacturing process of the transit buses are estimated with the EIO-LCA. In the EIO-LCA the average amount spent by a consumer on the product or service over its lifetime is estimated to determine the final demand for each sector. Then this monetary amount has to be converted into 1997 dollars (to correspond to the year of the EIO-LCA model) using the consumer price index (CPI) and equation. 5.1.

$$price_{1997} = price_{year} \times (\frac{CPI_{1997}}{CPI_{year}}) \tag{5.1}$$

The economic sector in EIO-LCA that matches to the manufacturing process of a bus is the Heavy Duty Truck Manufacturing (#336120)[1] sector. The input data required for the EIO-LCA include the price that a manufacturer sells the bus to the dealer and corresponds to the invoice price. The retail value for a 40 ft. DB and a 60 ft. BRT is $319,709 (2007$) and $550,000 (2002$), respectively. The invoice value of the DB and the BRT is reduced by approximately 16% (FTA 2007, TCRP 2002). The cost of the DB

[1] The North American Industry Classification System (NAICS) is the standard used by Federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. The U.S. Census Bureau assigns one NAICS code to each establishment based on its primary activity (generally the activity that generates the most revenue for the establishment.) NAICS is a 2 to 6 digit hierarchical classification system, offering five levels of detail. The first two digits designate the economic sector, the third digit designates the subsector, the fourth digit designates the industry group, the fifth digit designates the NAICS industry, and the sixth digit designates the national industry. A complete and valid NAICS code contains six digits (U.S. Census Bureau 2010a.)

and the BRT in 1997$ is estimated to be $207,536 and $411,404 as shown in equations 5.2 and 5.3. The CPI for 1997, 2002 and 2007 is 160.5, 179.9 and 207.3 respectively (DOL 2011.)

$$price_{1997} = 268{,}051 \times \left(\frac{160.5}{207.3}\right) = \$207{,}536 \tag{5.2}$$

$$price_{1997} = 461{,}131 \times \left(\frac{160.5}{179.9}\right) = \$411{,}404 \tag{5.3}$$

The emissions and energy inventories per VMT for the manufacturing stage associated with the vehicles are shown in Table 5.10. The results show that in terms of GHGs the most efficient vehicle is the ICEV with emissions approximately equal to 50 g/mile, more than 1.5 times less than those of a GPT. Advanced technologies, such as EV and PHEV have higher SO_x emissions compared with ICEV and HEV, which occur from the fabrication processes of materials such as aluminum and copper that are used for several components of the traction motor, the electronic controller and the generator. Additionally, NI-MH batteries that are used for HEV are responsible for higher SO_x emissions than for lead-acid batteries that are used for ICE based vehicles.

Table 5.10. Emissions and Energy Results for Vehicle Manufacturing

Indicators	Units	ICEV	HEV	FCV	EV	PHEV	GPT	GSUV	DB	BRT	CS	CS
		Camry	Prius	Clarity	Leaf	Volt	F-150	Explorer	New flyer	New flyer	Camry	Prius
CO2 (w/ C in VOC & CO)	*grams/ VMT*	50.4	54.6	61.8	60.9	55.9	80.8	80.3	240.8	477.4	50.4	54.6
CH4	*grams/ VMT*	0.090	0.093	0.103	0.100	0.092	0.146	0.143	0.039	0.078	0.090	0.093
N2O	*grams/ VMT*	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
GHGs	*grams/ VMT*	52.8	57.1	64.6	63.6	58.4	84.7	84.2	279.3	553.7	52.8	57.1
VOC	*grams/ VMT*	0.038	0.037	0.028	0.028	0.028	0.061	0.505	0.807	1.600	0.038	0.037
CO	*grams/ VMT*	0.305	0.297	0.212	0.209	0.189	0.556	0.492	3.194	6.332	0.305	0.297
NOx	*grams/ VMT*	0.081	0.085	0.093	0.088	0.082	0.124	0.131	0.622	1.233	0.081	0.085
PM10	*grams/ VMT*	0.097	0.098	0.093	0.096	0.094	0.160	0.149	0.179	0.355	0.097	0.098
SOx	*grams/ VMT*	0.155	0.262	0.255	0.328	0.321	0.232	0.217	0.687	1.362	0.155	0.262
Energy	*kj /VMT*	712	727	824	820	762	1,134	712	727	3,512	6,963	1,152

5.3.2. Fueling

GREET 1.7 was used for the fueling cycle; it is able to simulate different fuel production pathways and vehicle/fuel systems, according to the input data which may include:

- Fuel production options for fuel types
- Various fuel contents and market share percentages
- Various vehicle technologies
- Various electricity production pathways

The model estimates the energy use and emissions associated with:

- Primary energy production (feedstock recovery)
- Transportation and storage
- Fuel production
- Transportation, storage and distribution

The input data in GREET 1.7 applicable for this study are separated into the following sections:

- Selection of feedstock
- Selection of fuel options for simulation
- Selection of vehicle types for simulation (Section 5.2)

The production and distribution of different fuels, as mentioned in Chapter 2 are known as well-to-pump (WTP) activities. For this analysis the fuel production pathway options used are shown in Table 5.11.

Table 5.11. Fuel Pathway Options

Feedstock	Fuel
Petroleum	Conventional crude oil to conventional gasoline (CG)
Petroleum	Conventional crude oil to conventional diesel (CD)
U.S. Mix (Table 5.17)	Electricity
U.S. electricity generation mix via electrolysis at refueling stations	Gaseous hydrogen (GH_2)

The basic input parameters for simulating petroleum-based fuels are shown in Tables 5.12 and 5.13 for gasoline fuel, and in Tables 5.14 and 5.15 for diesel fuel.

Table 5.12. Reformulated (RFG), Conventional Gasoline Market Shares

Year	RFG %	CG %
2010	50.0%	50.0%

Table 5.13. Petroleum Production Efficiency for Gasoline Fuel

Petroleum	Efficiency
Crude Recovery	98.0%
CG Refining	87.7%
RFG Refining	87.20%

Table 5.14. Low-Sulfur (LSD), Conventional Diesel Market Shares

Year	LSD %	CD %
2010	100.0%	0.0%

Table 5.15. Petroleum Production Assumptions for Diesel Fuel

Petroleum	Efficiency
Crude Recovery	98.0%
LSD Refining	89.30%

The default hydrogen production is assumed to be produced by North American natural gas (NG) via steam methane reforming (SMR) at refueling stations. The basic input parameters for simulating hydrogen fuels are shown in Tables 5.16 and 5.17. Other feedstock sources may include:

- NG via SMR
- Solar energy via photovoltaic
- Nuclear energy via thermo-chemical water cracking (TCWC) using heat from a High-Temperature Gas-cooled Reactor (HTGR)
- Nuclear energy via high-temperature electrolysis of water
- Coal via gasification
- Biomass via gasification
- Ethanol (EtOH)
- Methane (MeOH)

Table 5.16. Gas H_2 Production: Central/Refueling Station Shares

Year	Central Production	Station Production
2010	0.0%	100.0%

The share for production of gaseous hydrogen from natural gas at a refueling station instead of a central plant can be revised because it might be contrary to land use and permitting. However, station production limits hydrogen transportation costs (i.e., transportation by pipelines or trucks.) Additionally, parasitic energy losses in hydrogen when transported with pipelines reduce the amount of energy available for useful purposes (Bossel 2006.)

Table 5.17. Gaseous Hydrogen Efficiency

Gaseous Hydrogen	Assumptions
Refueling station production withNG as feedstock	70.00%

Energy use and emissions of electricity generation in GREET are related to: (1) electricity usage in WTP activities, and (2) electricity use in vehicles powered exclusively or partially by electricity. For the first one, of the various power plant types, those fueled by residual oil, natural gas, coal, and biomass produce emissions at the plant site, besides emissions associated with production and delivery of the fuels to power plants. Although nuclear power plants do not produce air emissions at the plant site, emissions and energy use associated with the upstream production of uranium and its preparation stages are accounted for in GREET. Electricity generated from hydropower, solar, wind, and geothermal sources are treated as zero-emission plants in GREET. GREET does not include estimation of emissions associated with the construction of facilities.

There are two types of electricity generation mix, the marginal and the average mix. The marginal generation electricity mix (transportation use) is for generating and supplying electricity to the EVs and PHEVs for operation; and the average generation mix (stationary use) is used for all WTP activities, which include the production and distribution activities of different transportation fuels. For this dissertation, similar generation mixes are assumed, as shown in Table 5.18.

Table 5.18. Marginal and Average Electricity Generation Mix

Source	Percentage
Residual Oil:	1.1
Natural Gas:	18.3
Coal:	50.4
Nuclear Power:	20.0
Biomass Electricity:	0.7
Others :*	9.5

***Others include renewable sources as hydropower, solar, wind and geothermal.**

The basic input parameters for simulating electricity production are shown in Table 5.19.

Table 5.19. Electricity Production Parameters

Electricity Parameters	Values
Residual Oil Utility Boiler Efficiency	34.8%
NG Utility Boiler Efficiency	34.8%
NG Simple Cycle Turbine Efficiency	33.1%
NG Combined Cycle Turbine Efficiency	53.0%
Coal Utility Boiler Efficiency	34.1%
Electricity Transmission and Distribution Loss	8.0%
Energy intensity in HTGR reactors (MWh/g of U-235)	8.7
Energy intensity in LWR reactors (MWh/g of U-235)	6.9
Electricity Use of Uranium Enrichment (kWh/SWU*): Gaseous Diffusion Plants for LWR electricity generation	2,400
Electricity Use of Uranium Enrichment (kWh/SWU): Centrifuge Plants for LWR** electricity generation	50.0
Electricity Use of Uranium Enrichment (kWh/SWU): Gaseous Diffusion Plants for HTGR electricity generation	2,400
Electricity Use of Uranium Enrichment (kWh/SWU): Centrifuge Plants for HTGR*** electricity generation	50

*** SWU: Separative work units**
**** LWR: Light water reactor**
*****HTGR: High temperature gas-cooled reactor**

The emission and energy inventories per VMT for the feedstock and fueling stage associated with the vehicles are shown in Tables 5.20 and 5.21. The GHG emissions are higher for vehicles that use gasoline compared with alternative fuel vehicles (AFVs) at the feedstock recovery stage. However, at the fuel production stage, the GHG emissions for AFVs are increasing dramatically (i.e., 200 and 299 grams/VMT for EV and FCV, respectively) compared with gasoline based vehicles due to the production process. This is true especially for the production of electricity for EV. This result reveals the significance of upstream emissions produced in plants during electricity generation and the need to account for these. GHG emission patterns are similar to that of the energy consumption. However, total GHG emissions for the FCV (221.4 grams/VMT) show a more significant reduction compared with the HEV (47.5 grams/VMT). This is because hydrogen produced from NG is less carbon intensive than petroleum-derived gasoline on a per-energy-unit basis. Total energy consumption is estimated to be 1449 kj/VMT and 633 kj/VMT for the FCV and the HEV respectively.

Table 5.20. Emissions and Energy Results for Primary Energy Production

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	18.8	8.2	10.2	9.2	8.1	26.3	23.2	122.5	95.5	18.8	8.2
CH_4	*grams/ VMT*	0.509	0.222	0.445	0.407	0.220	0.712	0.628	2.280	1.779	0.509	0.222
N_2O	*grams/ VMT*	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.000	0.000
GHGs	*grams/ VMT*	31.7	13.8	21.4	19.4	13.7	44.3	39.1	180.1	140.5	31.7	13.8
VOC	*grams/ VMT*	0.019	0.008	0.011	0.022	0.008	0.027	0.024	0.087	0.068	0.019	0.008
CO	*grams/ VMT*	0.036	0.016	0.016	0.013	0.016	0.051	0.049	0.162	0.126	0.036	0.016
NO_x	*grams/ VMT*	0.135	0.059	0.045	0.054	0.058	0.189	0.167	0.605	0.472	0.135	0.059
PM_{10}	*grams/ VMT*	0.011	0.005	0.002	0.394	0.005	0.016	0.014	0.051	0.040	0.011	0.005
SO_x	*grams/ VMT*	0.045	0.020	0.022	0.028	0.020	0.063	0.053	0.203	0.158	0.045	0.020
Energy	*kj /VMT*	309	135	153	127	134	432	382	1,385	1,080	309	135

Table 5.21. Emissions and Energy Results for Fuel Production

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	73.1	32.0	194.3	297.1	31.7	102.4	90.4	257.6	200.9	73.1	32.0
CH_4	*grams/ VMT*	0.086	0.038	0.227	0.005	0.037	0.121	0.106	0.285	0.222	0.086	0.038
N_2O	*grams/ VMT*	0.006	0.003	0.001	0.004	0.002	0.008	0.007	0.004	0.003	0.006	0.003
GHGs	*grams/ VMT*	77.0	33.7	200.2	298.4	33.4	107.8	95.1	265.9	207.4	77.0	33.7
VOC	*grams/ VMT*	0.130	0.057	0.012	0.005	0.056	0.182	0.161	0.104	0.081	0.130	0.057
CO	*grams/ VMT*	0.042	0.018	0.039	0.065	0.018	0.058	0.058	0.148	0.115	0.042	0.018
NO_x	*grams/ VMT*	0.125	0.055	0.089	0.269	0.054	0.175	0.156	0.445	0.347	0.125	0.055
PM_{10}	*grams/ VMT*	0.049	0.021	0.069	0.019	0.021	0.068	0.060	0.162	0.126	0.049	0.021
SO_x	*grams/ VMT*	0.085	0.037	0.088	0.682	0.037	0.118	0.100	0.303	0.237	0.085	0.037
Energy	*kj /VMT*	1,138	498	1,296	2,144	493	1,593	1,406	3,631	2,832	1,138	498

5.3.3. Operation

Energy and emission indicators related to the operation stage include running of vehicles as well as processes that support the lawful usage of vehicles such as insurance, registration, license and taxes. For the operation stage, MOBILE6.2, GREET 1.7 and EIO-LCA were used to obtain results for all vehicles.

The emissions inventory generated in MOBILE6.2 disaggregates driving, startup, tires, brakes, evaporative, and idling components. In MOBILE6.2 the road type and vehicle speed can be simulated for different vehicle types and most of the output data are sensitive to such changes. Unlike most other MOBILE6.2 emission estimates, CO_2 emission estimates are not adjusted for speed, temperature, fuel content, or the effects of vehicle inspection maintenance programs. Fuel consumption and emissions do not follow a linear relationship with vehicle speed. The parabolic relationship of fuel energy use and speed for different vehicle works is shown in Figure 5.2 (Ross 1994) where the maximum and minimum energy consumption for different vehicle speeds can be estimated.

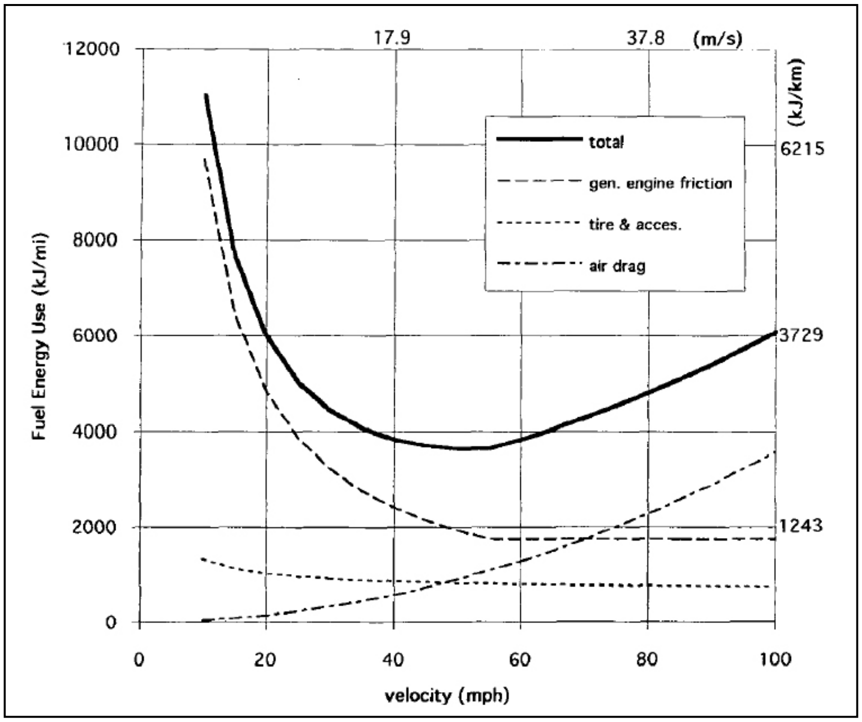

Figure 5.1. Fuel energy Use and Velocity Relationship

5.3.3.1.Running

Running includes driving, startup, tires, brakes and evaporative emissions. MOBILE6.2 model is used to estimate the emissions generated from gasoline vehicles. The arterial street was chosen and simulated in MOBILE6.2 as a road type, assuming an average travel speed of 27.3, 12.6 and 20.0 mph for passenger cars, DB and BRT respectively (TTI 2009, TCRP 2002, APTA 2009.) MOBILE6.2 does not generate estimates for energy, GHG and N_2O; therefore GREET estimates for N_2O and equations 5.4 and 5.5 are used for energy and GHG calculations, respectively.

$$E_{op} = \frac{(VMT \times E_c)}{Fuel\ \ efficiency} \tag{5.4}$$

$$GHG = \mathrm{GWP}_{\mathrm{CO_2}/i} \times CH_4 + \mathrm{GWP}_{\mathrm{CO_2}/i} \times N_2O + \mathrm{GWP}_{\mathrm{CO_2}/i} \times CO_2 \tag{5.5}$$

Where:

E_{op} is the operation energy of the vehicle in BTU

E_c is the combustion energy of a fuel (for fuel gas the E_c equals 125,000 BTU/gal (Davis et al. 2009)

VMT is the vehicle miles traveled

Fuel efficiency is expressed in miles per gallon (mpg)

$GWP_{CO2/i}$ is the Global Warming Potential of the GHG *i* relative to CO_2. The global warming potential of GHG relative to CO_2 for CH_4, N_2O and CO_2 is 25, 298 and 1 respectively, based on Intergovernmental Panel on Climate Change (IPCC 2001.)

The Reid vapor pressure (RVP), a common measure of and generic term for gasoline volatility is taken as 8.4 psi which is the average between maximum and minimum RVP values from EPA. The diesel sulfur fuel content was set to 15 parts per million (ppm) to comply with EPA Tier 2 low sulfur fuel standards which was implemented in late 2006. The fuel efficiency for all vehicle types is shown in Table 5.22. It is assumed that there is no deterioration of vehicle fuel economy performance during their lifetime. The minimum and maximum temperature is set to 22ºC (72ºF) and 33ºC (92ºF) respectively. Humidity is set to 115 grains per pound (grains/lb). Humidity, which affects NO_x emissions, is also used to calculate the heat index which affects utilization of air-conditioning and thereby CO and HC related air toxic emissions.

Table 5.22. Fuel Efficiency per Vehicle Model

	Vehicle Technology	Model	Urban Fuel Efficiency (mpg)
1	ICEV	Camry	22.0
2	HEV	Prius	48.0
3	FCV	Clarity	72.0
4	EV	Leaf	94.0
5	PHEV	Volt	35.0
6	GPT	F-150	15.0
7	GSUV	Explorer	17.0
8	DB	Newflyer	3.9
9	BRT	Newflyer	3.9
10	CSICEV	Camry	22.0
11	CSHEV	Prius	48.0

MOBILE6.2 does not generate emission estimates for AFV and does not generate GHGs and N_2O for any type of vehicle. Therefore, in addition to the energy inventory for AFVs, GREET is used to estimate emissions for AFVs, as well as GHGs and N_2O estimates for all vehicles. The emission estimations were calibrated based on the factors of MOBILE6.2 relative to GREET 1.7 for an ICEV. The default change rates relative to the baseline vehicles are estimated from multiple data sources, such as testing results or engineering analysis, which may change over time.

In GREET, SO_x emission factors for combustion technologies of all fuels, except for coal, biomass, crude and residual oil, are calculated by assuming that all sulfur contained in these process fuels is converted into sulfur dioxide (SO_2.) For having consistency in the results, SO_2 and SO_4 emissions from MOBILE6.2 are added and are presented as SO_x due to our interest in sulfur concentration.

The carbon fraction in VOC and CO is considered in the total CO_2 estimations, due to the assumption that eventually this part of carbon with further atmospheric chemical reactions (oxidation) will be converted to CO_2. All CO_2 estimations presented in this study include the carbon contained in VOC and CO, which are calculated from the set of equations 5.6.

$$CO_2 \; molecular\,weight = No.of\; atoms\, of\; each\; element \times (At.wt.of\;\; C + At.wt.\; of\; O) =$$
$$= 12 + 16 \times 2 = 44$$

$$C\,ratio\,of\; CO_2 = \frac{12}{44} = 0.27 \qquad C\,ratio\,of\; CO \;\; = \frac{12}{28} = 0.43$$

$$C\,ratio\,of\; VOC \; = \frac{12}{14.1} = 0.85 \tag{5.6}$$

$$CO_2 \;\; (with\; C\; in\, VOC\;\, and\, CO) = CO_2 + VOC \times \frac{C\,ratio\,of\; VOC}{C\,ratio\,of\; CO_2} + CO \times \frac{C\,ratio\,of\; CO}{C\,ratio\,of\; CO_2}$$

5.3.3.2.Idling

Idling emissions and energy requirements were estimated based on the assumption that the 2.5 mph emission factors can be applied to the entire idling time (equation 5.7.) An average passenger vehicle idles 7.5 minutes per day (CEC 2010.) Idling emissions rate and fuel consumption are calculated with equations 5.7 and 5.8 (EPA 2003b.)

$$Idling\; Emissions\, Rate\, (\frac{grams}{hour}) \; = \; Emissions\, at\; 2.5mph\, (\frac{grams}{mile}) \times Average\; speed\;\, (2.5mph) \tag{5.7}$$

$$Idling\;\; fuel\;\; consumption\;\, (liters\,/\,hour) \; = \; 0.35 \times ES + 0.33 \tag{5.8}$$

Where: *ES* is the vehicle engine size in liters (IFVT 2010.)

The energy consumed during idling is estimated by equation 5.9 and its units are shown in equation 5.10.

$$Idling\ energy = idling\ fuel\ consumption \times fuel\ energy \times \frac{idling\ time\ per\ year}{annual\ miles\ travelled} \quad (5.9)$$

$$\frac{BTU}{mile} = \frac{gallons}{hour} \times \frac{BTU}{gallon} \times \frac{\frac{hours}{year}}{\frac{miles}{year}} \quad (5.10)$$

For transit buses the idling emission rates for a 2001 Freitliner at 600 revolutions per minute and 18ºC are used (Storey et al. 2003.) The fuel consumption during idling status is estimated to be 0.53 g/h (Akcelik and Besley2003.) Transit bus idling time includes time spent idling at terminals in maintenance shops, turnaround time, and emergency breaks time. A typical bus that is in service for 50h/week may idle for 4 hours/week (Ziring 2008.) Idling time is calculated to be 208 hours/year for a DB and 104 hours/year for a BRT system according to the assumption that BRTs reduce idling time by 50% (ZF 2008.)

GREET 1.7 is used to estimate the energy inventory of vehicles, known as the pump-to-wheel activities. GREET 1.7 does not account for speed changes along a corridor; hence energy inventory remains constant for different traffic conditions. Energy (BTU/mile) is estimated based on the fuel efficiency (mpg) of every vehicle. GREET by default accounts for deterioration in the performance of vehicles by using values for vehicle models five year earlier than the desired simulation calendar year. On average, half lifetime of a light-duty vehicle is about five years in the U.S. To avoid errors in simulation, the year 2010 was used as the simulation year to enter vehicle performance and fuel data. The emission and energy inventories per VMT for running and idling vehicles are shown in Table 5.23 and 5.24.

As mentioned earlier, unlike most other MOBILE emission estimates, CO_2 emission estimates are not adjusted for speed, temperature or fuel content. MOBILE6.2 offers the option to model average speed distribution by hour and type of roadway. MOBILE6.2 accepts vehicle travel data specific to the geographical location of application. VMT fractions can be allocated to specific vehicle types or VMT distribution across 14 preselected average speed ranges for each of the 24 hours of the day for each scenario. Congestion or variable traffic conditions can be accounted in emissions modeling (i.e., for gasoline and diesel vehicles) when data are known. This study uses a single average speed value, rather an average speed distribution. For specific projects, where the VMT distribution over average speeds is known, the results can be more accurate.

Table 5.23. Emissions and Energy Results for Vehicle Running

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	436.1	198.5	0.0	0.0	304.3	587.7	526.6	2,618.1	2,043.0	436.1	198.5
CH_4	*grams/ VMT*	0.031	0.031	0.00	0.000	0.029	0.066	0.039	0.036	0.032	0.031	0.031
N_2O	*grams/ VMT*	0.012	0.012	0.00	0.000	0.012	0.012	0.012	0.012	0.012	0.012	0.012
GHGs	*grams/ VMT*	440.5	202.9	0.0	0.0	308.6	592.9	531.1	2,622.5	2,043.1	440.5	202.9
VOC	*grams/ VMT*	0.791	0.769	0.00	0.000	0.764	1.472	0.825	0.771	0.693	0.791	0.769
CO	*grams/ VMT*	7.110	7.110	0.00	0.000	7.110	11.510	7.830	3.921	3.418	7.110	7.110
NO_x	*grams/ VMT*	0.590	0.590	0.00	0.000	0.58	1.128	0.706	8.399	8.569	0.590	0.590
PM_{10}	*grams/ VMT*	0.025	0.025	0.021	0.020	0.027	0.026	0.025	0.198	0.198	0.025	0.025
SO_x	*grams/ VMT*	0.008	0.004	0.00	0.000	0.005	0.010	0.010	0.20	0.020	0.008	0.004
Energy	*kj /VMT*	5,508	2,748	1,970	1,517	3,844	8,792	7,128	37,522	29,267	5,508	2,748

Table 5.24. Emissions and Energy Results for Vehicle Idling

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	11.9	9.6	0.0	0.0	8.3	19.1	15.1	23.8	11.9	7.5	6.0
GHGs	*grams/ VMT*	11.9	9.6	0.0	0.0	8.3	19.1	15.1	23.8	11.9	7.5	6.0
VOC	*grams/ VMT*	0.065	0.065	0.000	0.000	0.065	0.104	0.057	0.016	0.008	0.041	0.041
CO	*grams/ VMT*	0.262	0.262	0.000	0.000	0.262	0.366	0.243	0.149	0.074	0.164	0.164
NO_x	*grams/ VMT*	0.013	0.013	0.000	0.000	0.013	0.021	0.014	0.392	0.196	0.008	0.008
PM_{10}	*grams/ VMT*	0.0001	0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	0.0042	0.0021	0.0001	0.0001
Energy	*kj /VMT*	169	135	61	47	115	273	219	253	197	106	85

5.3.3.3.Fixed Costs

Fixed costs for vehicle usage include insurance, license fees and taxes. Costs include all governmental taxes and fees payable at time of purchase, as well as fees due each year to keep the vehicle licensed and registered. Costs are computed on a national average basis. EIO-LCA method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in the economy. The fixed costs have few supplier impacts and therefore the impact to environment is not going to be significant.

Emissions and energy inventory associated with these processes are obtained from EIO-LCA by using the Insurance Carriers (#524100) sector. Finance charges are assumed to have few supplier impacts and are not included in the analysis. Insurance cost for passenger vehicles is based on a full-coverage policy for a married 47-year-old male with a good driving record and commuting three to 10 miles daily to work. The policy includes $100,000/$300,000 coverage with a $500 deductible for collision and a $100 deductible for comprehensive coverage.

License, registration and taxes costs include all governmental taxes and fees payable at time of purchase, as well as fees due each year to keep the vehicle licensed and registered. The final demand by each economic sector is determined by estimating the total amount spent on the service, and then using the consumer price index (CPI) to convert this value into 1997$ to correspond to the year of EIO-LCA model. The annual insurance cost for an ICEV is estimated to be $943 (2007$) (AAA 2007.) Vehicle annual registration, driving license, and taxes for an ICEV are estimated to be $544 (2007$) (AAA 2007.) Insurance, annual registration, driving license, and taxes costs for other vehicles are extrapolated from vehicle weights. It is assumed that the insurance is constant through the years. For CS programs the insurance cost of a rental vehicle ranges from $4,800 to $6,000 per vehicle per year. Thereby we use the average value of $5,400 per vehicle year (TCRP 2005.) The emission and energy inventories per VMT for the feedstock and fueling stage associated with the vehicles are shown in Tables 5.25 and 5.26.

Table 5.25. Emissions and Energy Results for Vehicle Insurance

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	5.0	4.6	5.4	5.3	5.7	8.6	6.8	9.6	18.1	19.1	19.1
CH_4	*grams/ VMT*	0.036	0.033	0.039	0.038	0.041	0.063	0.049	0.070	0.132	0.139	0.139
N_2O	*grams/ VMT*	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001
GHGs	*grams/ VMT*	5.8	5.4	6.3	6.2	6.7	10.1	8.0	11.4	21.4	22.6	22.6
VOC	*grams/ VMT*	0.011	0.010	0.012	0.012	0.013	0.020	0.015	0.023	0.044	0.046	0.046
CO	*grams/ VMT*	0.064	0.059	0.069	0.068	0.073	0.111	0.087	0.126	0.237	0.250	0.250
NO_x	*grams/ VMT*	0.015	0.014	0.016	0.016	0.017	0.026	0.021	0.031	0.059	0.062	0.062
PM_{10}	*grams/ VMT*	0.002	0.002	0.003	0.003	0.003	0.004	0.003	0.006	0.011	0.011	0.011
SO_x	*grams/ VMT*	0.014	0.012	0.015	0.014	0.016	0.023	0.018	0.028	0.052	0.055	0.055
Energy	*kj /VMT*	70	64	76	74	80	121	95	139	262	276	276

Table 5.26. Emissions and Energy Results for Vehicle License, Registration and Taxes

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	4.4	4.1	4.8	4.7	5.0	7.1	6.0	9.4	17.7	4.4	4.1
CH_4	*grams/ VMT*	0.022	0.020	0.024	0.024	0.025	0.036	0.030	0.047	0.089	0.022	0.020
N_2O	*grams/ VMT*	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.000
GHGs	*grams/ VMT*	5.0	4.6	5.4	5.3	5.7	8.1	6.8	10.7	20.1	5.0	4.6
VOC	*grams/ VMT*	0.006	0.005	0.006	0.006	0.006	0.009	0.008	0.012	0.022	0.006	0.005
CO	*grams/ VMT*	0.041	0.038	0.045	0.044	0.047	0.067	0.056	0.088	0.166	0.041	0.038
NO_x	*grams/ VMT*	0.013	0.012	0.014	0.014	0.015	0.021	0.018	0.028	0.052	0.013	0.012
PM_{10}	*grams/ VMT*	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.005	0.009	0.002	0.002
SO_x	*grams/ VMT*	0.012	0.011	0.013	0.013	0.014	0.019	0.016	0.025	0.048	0.012	0.011
Energy	*kj /VMT*	69	64	75	73	79	112	95	148	279	69	64

5.3.4. Maintenance

Vehicle maintenance includes the maintenance and disposal of vehicle parts. Disposal takes into account the dismantling process required for disposal. The energy required for dismantling vehicles for disposal was estimated to be approximately 1.48 Gj/vehicle for a vehicle weighing 3,000 lb (Stodolsky et al. 1995.) This value does not include material recovery processes or combustion for energy recovery. For disposal the model takes into account the energy required and emissions generated during recycling of scrap materials back into original materials for reuse. GREET examines the energy use and emissions associated with vehicle disposal processes including vehicle disposal recycling.

EIO-LCA and the Automotive Mechanical and Electrical Repair and Maintenance (#81111) and the Tire Manufacturing (#32621) sectors are used to estimate the energy and emissions inventory associated with these services. The maintenance costs of the passenger vehicles are estimated based on ICEV maintenance cost of 0.047 $/mile (2007$) and the assumption that an EV has fewer mechanical parts than an ICEV.

The ICEV requires a wide range of maintenance, from frequent oil changes, filter replacements, periodic tune ups, and exhaust system repairs, to the less frequent component replacement, such as the water pump, fuel pump, alternator, etc. The EV's maintenance requirements are lower and therefore the maintenance costs are lower. The electric motor has one moving part, the shaft, which is very reliable and requires little or no maintenance. The controller and charger are electronic devices with no moving parts, and they require little or no maintenance. State-of-the-art Li-Ion batteries used in current electric vehicles are sealed and are maintenance free. New batteries extend the life of the battery pack which may eliminate the need to replace the battery pack during the life of the vehicle. Figure 5.2 shows vehicle components for a gasoline and electric vehicle (DOE 2010.)

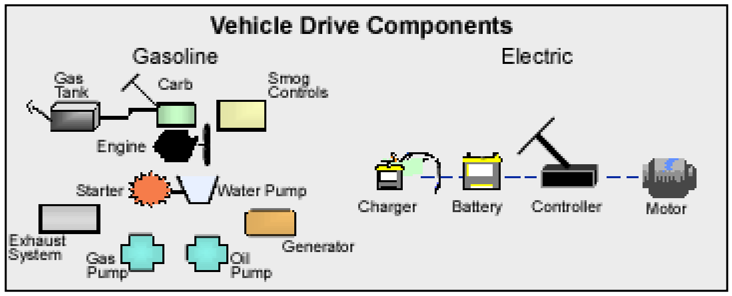

Figure 5.2. Vehicle Drive Components

The maintenance cost for AFVs are assumed to be half of the ICEV cost, thus it is 0.024$/mile. The HEV embraces all the components of an ICEV and it is estimated that its maintenance cost is 0.045 $/mile based on the maintenance schedule for a HEV relative to an ICEV (Toyota Service 2010.) SUVs and GPTs' maintenance cost is 0.055$/mile and for CS is assumed that the maintenance cost is estimated according to the vehicle model that is used for leasing. Tire cost for passenger vehicles is 0.008 $/mile (2007$). For the DB and the BRT the maintenance cost is $0.46/mile (2006$) and includes the following (Chandler and Walkwicz 2006.):

- Air system
- Axles, wheels, and drive shaft
- Brakes
- Cab, body, and accessories – includes body repairs following accidents, glass, and paint; cab and sheet metal repairs on seats and doors
- Frame, steering, and suspension – includes steering and suspension repairs

- Heating, ventilation, and air-conditioning
- Lighting
- Preventive maintenance inspections – labor for inspections during preventive maintenance
- Propulsion-related systems – repairs for exhaust, fuel, and engine; electric motors, traction batteries, and propulsion control; non-lighting electrical (charging, cranking, and ignition); air intake, cooling, hydraulics, and transmission
- Tires

Emission output data from EIO-LCA produce (CO_2e) or the carbon dioxide equivalent. CO_2e is a quantity that describes, for a given mixture and amount of GHG, the amount of CO_2 that would have the same GWP, when measured over a specified timescale (generally, 100 years).The CO_2e for a gas is obtained by multiplying the mass and the GWP of the gas. For example, the GWP for methane over 100 years is 25 and for nitrous oxide 298. This means that emissions of 1 million metric tonnes of CH_4 and N_2O respectively are equivalent to emissions of 25 and 298 million metric tonnes of CO_2 (IPCC 2001.)

Therefore for EIL-OCA results, the CH_4 and N_2O emissions are divided by 25 and 298 respectively to get the actual weights. The emission and energy inventories per VMT for the maintenance and tires, disposal and recycling stage associated with the vehicles are shown in Tables 5.27 and 5.28, respectively. Total emissions and energy inventories for vehicle lifetime weighted per VMT and PMT are shown in Tables 5.29 and 5.30, respectively. Figures 5.4 and 5.5 show the energy inventory per VMT and PMT, respectively, for all vehicle life cycle stages.

Table 5.27. Emissions and Energy Results for Vehicle Maintenance

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	17.5	16.5	11.2	11.2	16.5	19.7	20.2	136.0	136.0	17.0	17.0
CH_4	*grams/ VMT*	0.080	0.075	0.048	0.048	0.075	0.090	0.092	0.028	0.028	0.077	0.077
N_2O	*grams/ VMT*	0.002	0.002	0.001	0.001	0.002	0.002	0.002	0.000	0.000	0.002	0.002
GHGs	*grams/ VMT*	21.5	20.2	13.5	13.5	20.2	24.2	24.9	159.8	159.8	20.9	20.9
VOC	*grams/ VMT*	0.054	0.050	0.033	0.033	0.050	0.061	0.062	0.476	0.476	0.052	0.052
CO	*grams/ VMT*	0.226	0.214	0.153	0.153	0.214	0.254	0.260	1.642	1.642	0.221	0.221
NO_x	*grams/ VMT*	0.043	0.040	0.026	0.026	0.040	0.048	0.050	0.376	0.376	0.042	0.042
PM_{10}	*grams/ VMT*	0.012	0.012	0.009	0.009	0.012	0.014	0.014	0.081	0.081	0.012	0.012
SO_x	*grams/ VMT*	0.046	0.043	0.027	0.027	0.043	0.051	0.053	0.413	0.413	0.044	0.044
Energy	*kj /VMT*	250	236	163	163	236	282	289	1,862	1,862	244	244

Table 5.28. Emissions and Energy Results for Vehicle Disposal

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	2.5	2.5	1.8	1.8	1.8	5.0	4.2	7.3	13.8	1.6	1.6
CH_4	*grams/ VMT*	0.003	0.003	0.002	0.002	0.002	0.007	0.006	0.010	0.019	0.002	0.002
N_2O	*grams/ VMT*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GHGs	*grams/ VMT*	2.6	2.6	1.9	1.9	1.9	5.2	4.3	7.6	14.3	1.7	1.7
VOC	*grams/ VMT*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000
CO	*grams/ VMT*	0.001	0.001	0.000	0.000	0.000	0.001	0.004	0.002	0.004	0.000	0.000
NO_x	*grams/ VMT*	0.003	0.003	0.002	0.002	0.002	0.005	0.005	0.008	0.015	0.002	0.002
PM_{10}	*grams/ VMT*	0.003	0.003	0.002	0.002	0.002	0.007	0.006	0.010	0.019	0.002	0.002
SO_x	*grams/ VMT*	0.006	0.006	0.004	0.004	0.004	0.012	0.008	0.017	0.032	0.004	0.004
Energy	*kj /VMT*	32	32	23	23	23	64	53	93	175	20	20

Table 5. 29 Emissions and Energy Results for Vehicle Lifetime per VMT

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ VMT*	619.8	330.6	289.5	390.1	437.4	856.1	772.8	3,425.2	3,014.4	628.1	341.2
CH_4	*grams/ VMT*	0.857	0.516	0.889	0.625	0.522	1.235	1.094	2.796	2.379	0.956	0.624
N_2O	*grams/ VMT*	0.021	0.018	0.004	0.007	0.018	0.025	0.024	0.021	0.021	0.022	0.019
GHGs	*grams/ VMT*	648.8	350.0	313.2	408.2	456.9	895.6	808.6	3,561.2	3,176.6	659.6	363.4
VOC	*grams/ VMT*	1.069	0.961	0.078	0.081	0.949	1.881	1.603	2.296	2.993	1.079	0.973
CO	*grams/ VMT*	7.946	7.886	0.467	0.484	7.801	12.808	8.914	9.432	12.115	8.034	7.979
NO_x	*grams/ VMT*	1.018	0.871	0.286	0.469	0.861	1.736	0.579	10.905	11.318	1.058	0.915
PM_{10}	*grams/ VMT*	0.202	0.168	0.201	0.546	0.166	0.298	0.275	0.695	0.840	0.209	0.176
SO_x	*grams/ VMT*	0.370	0.394	0.424	1.096	0.458	0.527	0.475	1.696	2.322	0.408	0.436
Energy	*Mj/VMT*	8.258	4.638	4.640	4.987	5.766	12.793	10.817	48.648	43.020	8.382	4.796

Table 5.30. Emissions and Energy Results for Vehicle Lifetime per PMT

Indicators	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
CO_2 (w/ C in VOC & CO)	*grams/ PMT*	540.9	288.5	252.6	340.4	381.7	777.2	550.2	326.2	126.1	137.0	74.4
CH_4	*grams/PMT*	0.748	0.450	0.776	0.546	0.456	1.121	0.779	0.266	0.100	0.209	0.136
N_2O	*grams/PMT*	0.019	0.015	0.003	0.006	0.016	0.022	0.017	0.002	0.001	0.005	0.004
GHGs	*grams/PMT*	566.2	305.4	273.4	356.2	398.7	813.1	575.7	339.2	132.9	143.9	79.3
VOC	*grams/PMT*	0.933	0.839	0.068	0.071	0.828	1.708	1.141	0.219	0.125	0.236	0.212
CO	*grams/PMT*	6.934	6.882	0.407	0.423	6.808	11.627	6.346	0.898	0.507	1.753	1.741
NO_x	*grams/PMT*	0.888	0.760	0.249	0.409	0.752	1.576	0.412	1.039	0.474	0.231	0.200
PM_{10}	*grams/PMT*	0.176	0.147	0.175	0.476	0.145	0.270	0.196	0.066	0.035	0.046	0.038
SO_x	*grams/PMT*	0.323	0.344	0.370	0.957	0.400	0.478	0.338	0.162	0.097	0.089	0.095
Energy	*Mj/PMT*	7.206	4.048	4.049	4.352	5.032	11.614	7.701	4.633	1.800	1.829	1.046

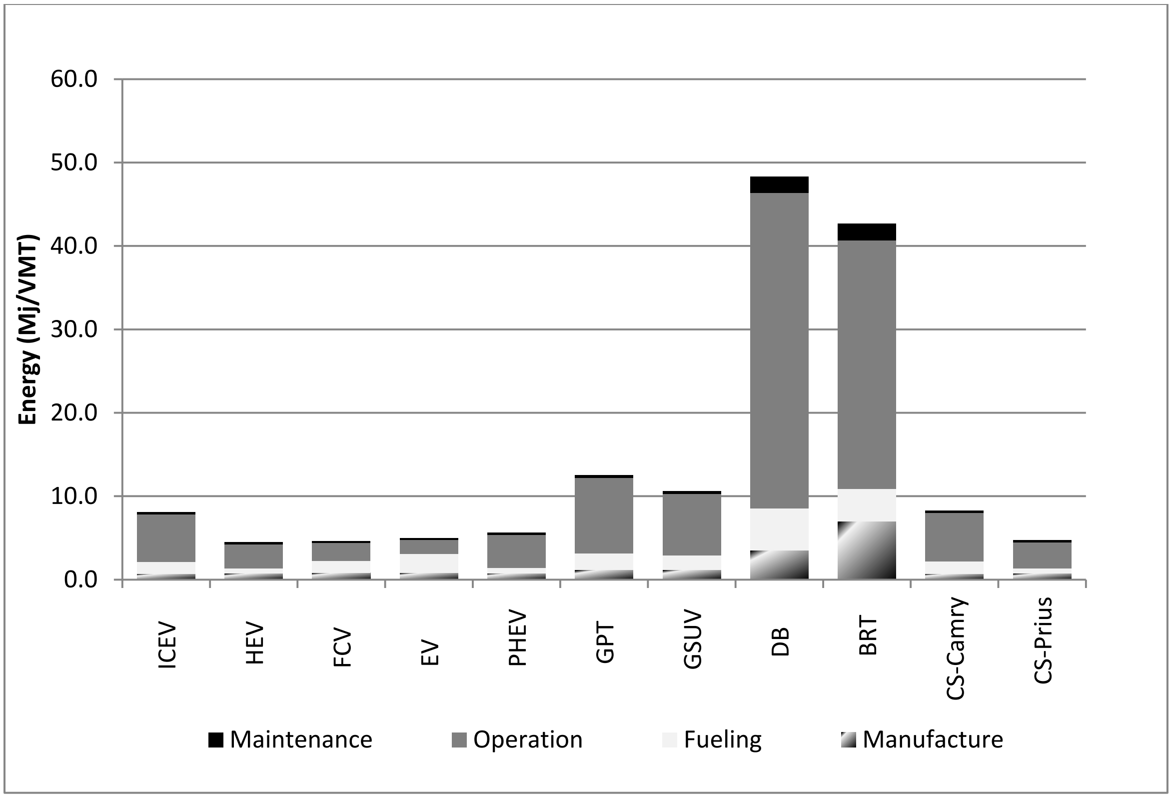

Figure 5.3. Energy Inventory per VMT

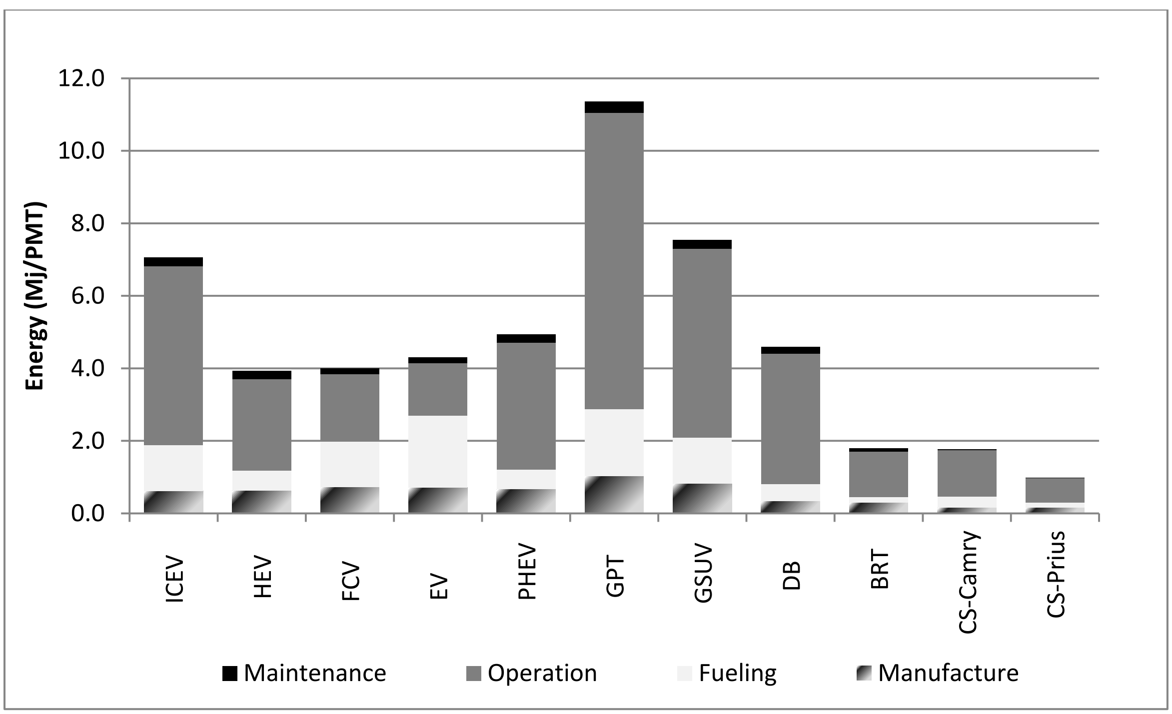

Figure 5.4. Energy Inventory per PMT

The last sustainability indicator for the environmental dimension is vehicle noise. Noise is an outcome of all attributes and it has an impact on human health. Herein, noise is measured in decibels (dB), it is considered only for vehicle operation and its value for each vehicle type is assumed to be representative for average urban speeds of 28 mi/hr at a distance of 15 m. At speeds greater than 30 mi/hr vehicles with advanced propulsion offer negligible noise benefits because at higher speeds noise is generated mostly by the tire/road interaction (Fleming et al. 2000) and vehicle aerodynamics. Noise levels at 28 mi/hr are estimated from existing literature (Mathews 2005, NPC 1989.)

5.4. Technology Sustainability Indicators

Technology sustainability indicators reveal how vehicle technology developments improve the vehicle – user experience and therefore sustain a transportation vehicle in the network. Selected sustainability indicators for technology are quantified as follows:

a) **Life expectancy** refers to the expected lifetime of the vehicle. This is fundamental to developing annual measures based on proposed indicators. Although the average lifetime of new vehicle technologies (e.g., fuel cell vehicles) has not been established yet, it is assumed to be the same with the vehicle's battery lifetime which reflects FreedomCAR Program Research and Development goals of a 15 year lifetime (Burnham et al. 2009.)

b) **Capacity** refers to the relative passenger carrying ability compared with the maximum capacity of a vehicle class; it is expressed as a percentage for each vehicle type. For transit buses the total number of passengers (i.e., sitting and standees) is considered based on the assumption that the internal vehicle design should maximize the number of passengers that each bus can carry (Chevrolet 2010, Nissan 2010, Ford 2010, Honda 2010, Toyota 2010, New Flyer 2010.) Values can be replaced with local data.

c) **Frequency of fueling** refers to the time a user spends during fueling/charging of a vehicle over its lifetime; a higher number is less desirable for the user. This indicator is significant for short range modes. It is estimated by dividing the lifetime miles of a vehicle by the product of fuel tank capacity and fuel efficiency. For EVs the fuel tank is replaced by a battery array. PHEVs are assumed that they are driven a fixed number of miles in electric mode before the gas generator is introduced to create electricity for additional miles. A user needs six minutes in a gas or hydrogen station to complete the fueling. For EVs it is assumed that 10% of the annual charging requirements obligate the user to stop for 26 minutes to charge the vehicle (Nissan 2010.) The remaining 90% of charging requirements occur while the vehicle is parked. This assumption is sensitive to public policies and economies and it might change when more and/or faster charging stations (i.e., 480V) are available for public use.

d) **Maintenance frequency** refers to the time a user spends on vehicle maintenance. The ICEV is the base which is required to be maintained 22 times in its lifetime; its owner spends two hours each time to drop-off and retrieve the vehicle. Additional time losses due to mode shift are not included. Maintenance intervals for the rest of the vehicles are estimated based on additional or fewer mechanical parts that each vehicle technology embrace (Toyota Service 2010, Trust my Mechanic 2010.) For example three battery changes are assigned for gasoline based vehicles, two for the HEV and none for the EV, the FVC and the PHEV. For transit buses it is assumed that each one requires an average of 260 hours per year for maintenance (Chandler and Walkowicz 2006.)

e) **Vehicle storage** when not in use is a fundamental requirement. The space occupied by the vehicle depends on the operational characteristics of the vehicle, such as hours of operation, headway, etc. and it can change for specific transportation conditions. The exact length and width for each vehicle are considered to estimate their total area.

f) **Engine power** refers to the maximization of vehicle power and it is expressed as the ratio of vehicle torque and weight. It is significant technology indicator as it shows how technological advances reduce the vehicle weight (i.e., material quantities and types) and maintain or increase vehicle power that improves vehicle performance. Torque was selected to represent engine ability as a more appropriate measure of ability for diesel and electric motors. Power of gasoline engines is high but it is delivered at high revolutions that are very seldom reached in urban travel.

g) **Supply** refers to the number of persons that can be moved per hour per vehicle. It is a generalized term for vehicular mode capacity and it is measured in passengers per hour per vehicle. This indicator accepts input only for local transportation projects.

5.5. Economy Sustainability Indicators

Economy relates to the promotion of vibrant and independent economy. Economy sustainability indicators reveal how vehicle monetary parameters may affect vehicle utilization and therefore make sustainable or unsustainable a transportation vehicle for a chosen network. Selected sustainability indicators for economy sustainability dimension are quantified as follows:

a. **Manufacturing cost** represents the invoice price of a vehicle. The invoice price is the price a car dealer pays the manufacturer; it is constant for every dealer in the U.S. For public transit buses the invoice price was 90% of the Manufacturer Suggested Retail Price (MSRP) (Edmunds 2002, CLG 2008.) Economies of scale are likely to play a significant role in market penetration rates for alternative fuel vehicles. Improved battery technologies, reduced fuel and material costs, combined with increased supporting infrastructure for alternative fuel vehicles, including FCV, EV and PHEV, may result in wider public acceptability. Alternative fuel vehicles demand may increase and in the long run average purchase costs should decrease.

b. **Operation cost** includes the cost for fueling/charging the vehicle, insurance, license, registration and taxes (AAA 2007, DOE 2009, III 2010.) The ICEV is considered as the base vehicle, and insurance, license, registration and tax costs for the rest of the vehicles are estimated based on their weight. Costs are described in section 5.3.3.3 and they are computed on a U.S. national average basis. Passenger fares for DB and BRT were estimated to be $1.43/trip and $1.73/trip based on the average adult base cash fare (APTA 2010.) For car share, an average of 5.5 miles/hour of city CS usage and an hourly average cost of $3.50/hour in addition to $0.35/mile charging (2004$) is assumed (TCRP 2005.) Indicator values can be replaced with local data.

c. **Maintenance cost** refers to the average cost that is required to maintain the vehicle over its lifetime. Mechanical parts and tires are included for all vehicle types (Burnham et al. 2006, AAA 2007.)

d. **Public subsidy** refers to the portion covered by taxpayers. For light-duty vehicles it refers to the federal tax credits and for public transit buses it refers to the subsidy required to operate and maintain each vehicle (DOE 2009, APTA 2009.) We assumed that the same federal income tax credit will be applied to all alternative fuel vehicles including the FCV when it will be available for purchasing. (In 2009, two types of light duty FCVs became available only for leasing and only in California.) Subsidies for DB and BRT were estimated to be $0.27/PMT and $0.12/PMT, respectively (APTA 2009.) Indirect costs to users in the form of property taxes to subsidize streets are excluded in this assessment. Indicator values can be replaced with local data.

e. **Parking cost** refers to the national average monthly unreserved parking rate per vehicle (Colliers International 2010.) For owners of advanced technology vehicles (FCV, EV, PHEV) it is assumed that free parking is offered to individuals or small businesses in designated downtown parking garages and surface parking lots (Hybrid Cars 2010.) Indirect costs in the form of property taxes or to users of a specific land use (e.g., University, hotel etc.) internalized in product/service prices to subsidize those free of charge spaces are excluded. Indicator values can be replaced with local data.

f. **Job opportunities** refer to the number of new job positions that will be created when a new transportation vehicle is introduced. It is measured in number of job when vehicle's market increases by 1%. This indicator accepts input only for local transportation projects.

5.6. Users Sustainability Indicators

Users sustainability indicators reveal important parameters of vehicles that users consider when they choose a vehicle. Vehicles that are not chosen will be unsustainable and they will deteriorate overall transportation sustainability. Selected sustainability indicators for users are quantified as follows:

a. **Mobility** is the provision of social and economic opportunities by the transportation network. The mobility indicator is expressed as the sum of person hours of travel (PHT) within the origin-destination pairs with the heaviest demand for a transportation network or as the sum of PHT for a specific corridor, using the same mode type. Values can only be generated for specific projects.

b. **Demand** refers to the types of vehicle users choose to satisfy their mobility needs and they are expressed as a percentage of vehicle type shares (Rodrigue et al. 2009.)

c. **Delay** is defined as the real travel time, which includes access to the vehicle, recurrent, weather related, incident and work zone congestion plus the time to park (it includes walk, wait and commute by mass transit), minus the travel time of a vehicle when it travels at 30 mi/hr. It is expressed in minutes per trip for specific origin-destination trips or in vehicle hours for a network. Values can only be generated for specific projects.

d. **Global availability** refers to the time during which a vehicle is not available to its potential users during a day. It is expressed as an annual percentage. It is estimated by dividing the total hours a vehicle is unavailable per year by the total number of hours in a year. The unavailable hours for light-duty vehicles are estimated by multiplying the time it takes to fuel/charge a vehicle times the fueling/charging frequency per year. We assumed that transit buses are not in operation for five hours per day (from midnight to 5 am.) Indicator values can be changed based on regional or local requirements.

e. **Reasonable availability** refers to the time during which a vehicle is not available to its potential users during the 19 hours between 5 am and 12 am per day when 98.8% of total trips occur (BTS 2001). It is expressed as an annual percentage. It is assumed that an EV requires 7 hours and a PHEV requires 4 hours per charging cycle at 220/240V starting from a depleted battery. It is assumed that transit buses are fully fueled upon start of service and they do not require fueling until the end of their shift (Chevrolet, Nissan 2010.) Values can be replaced with local data.

f. **Equity of access** refers to the number of types of vehicles that serve specific origin-destination pairs with heaviest, lightest and average demand. It is expressed as the sum of vehicle types serving an origin-destination pair (i.e., 1 if service is provided, 0 if not) and it is applicable only to local projects.

g. **Comfort and convenience** is represented by four indicators. Passenger and cargo space available to each user in a vehicle is expressed in liters per passenger; leg room space is expressed in centimeters, and seated probability indicator is expressed as the likelihood for a passenger to be seated during the trip. For transit buses it is assumed that the space under seats is the cargo space assigned to each passenger and for passenger space it is assumed that the internal height of buses scales from 2.44 meters to the front to 1.96 meters to the back and its width is 2.54 meters uniformly (Chevrolet 2010, Nissan 2010, Ford 2010, Honda 2010, Toyota 2010, New Flyer 2010, Zimmerman and Levinson 2004.)

h. **Fueling opportunities** refer to the available locations at the present time for fueling or charging a vehicle. It is expressed by the number of gas stations, hydrogen stations, or public electric charge stations. For hydrogen and electric stations both private and public stations in operation are considered (U.S. Census Bureau 2002, U.S. DOE 2010). This indicator is not applicable to public transit. Values can be replaced with local data.

Legal framework and local restrictions sustainability indicators have no role in a generic evaluation of urban models. The quantified life cycle sustainability indicators for each vehicle type per VMT and PMT are shown in Tables 5.31 to 5.32 and Tables 5.33 to 5.34 respectively. Results are presented weighted both per VMT and PMT to show the importance in the formulation of policies related to vehicle movements versus people movements. These are critical in the analysis of transit modes, HOT lanes, carpools, CS programs, etc.

The quantified indicators and their units are shown in Tables 5.31 to 5.34 for each sustainability dimension. The five sustainability dimensions are the goals for urban transportation vehicles which guide decision makers in enhancing sustainability performance. Plus and minus signs show the positive and negative utility, respectively, for the corresponding sustainability indicator (i.e., the greater the absolute value of the indicator the more positive or negative impact it has.)

Buses as expected, due to their size are the technologies with the highest energy consumption per VMT. When energy consumption is weighted per PMT the most energy demanding vehicles are found to be the GPT and the GSUV with energy consumption of 11.61 and 7.70 Mj/PMT, respectively. The vehicles with the lowest energy consumption over their lifetimes per VMT, are the HEV and the FCV. Their energy requirements are 44% lower than the energy requirements of an ICEV, and 64% lower than that of a GPT.

The CS program with HEV technology and the BRT system have the lower energy consumption per PMT.

Table 5.31. Vehicle Sustainability Indicators for Environment and Technology (VMT)

Sustainability Category	Objectives	Indicators	Code +/-	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Environment	Minimize global warming	CO_2 (w/ C in VOC & CO)	-	*grams/VMT*	620	331	289	390	437	856	773	3,425	3,014	628	341
		CH_4	-	*grams/VMT*	0.86	0.52	0.89	0.63	0.52	1.23	1.09	2.80	2.38	0.96	0.62
		N_2O	-	*grams/VMT*	0.02	0.02	0.00	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		GHGs	-	*grams/VMT*	649	350	313	408	457	896	809	3,561	3,177	660	363
	Minimize air pollution	VOC	-	*grams/VMT*	1.07	0.96	0.08	0.08	0.95	1.88	1.60	2.30	2.99	1.08	0.97
		CO	-	*grams/VMT*	7.95	7.89	0.47	0.48	7.80	12.81	8.91	9.43	12.11	8.03	7.98
		NO_x	-	*grams/VMT*	1.02	0.87	0.29	0.47	0.86	1.74	0.58	10.91	11.32	1.06	0.91
		PM_{10}	-	*grams/VMT*	0.20	0.17	0.20	0.55	0.17	0.30	0.28	0.70	0.84	0.21	0.18
		SO_x	-	*grams/VMT*	0.37	0.39	0.42	1.10	0.46	0.53	0.47	1.70	2.32	0.41	0.44
	Minimize noise	Noise	-	*dB*	61	57	57	57	57	69	64	78	78	61	57
Technology	Maximize lifetime service	Vehicle lifetime	+	*years*	10.6	10.6	15	15	15	9.6	9.6	12	12	2	2
	Maximize used resources	Capacity	+	*percentage*	100%	100%	80%	100%	80%	100%	100%	92%	99%	100%	100%
	Minimize time losses	Fuel frequency	-	*mins/VMT*	0.015	0.011	0.021	0.028	0.016	0.015	0.015	NA	NA	0.015	0.011
		Maintenance freq.	-	*mins/VMT*	0.022	0.020	0.008	0.007	0.014	0.024	0.024	0.031	0.031	0.060	0.047
	Minimize land consumption	Vehicle storage	-	*m^2/passenger*	7.6	6.8	7.8	6.9	6.7	9.8	7.1	3.0	2.0	1.9	1.7
	Maximize vehicle performance	Engine power	+	lb.ft./lb	0.050	0.050	0.053	0.059	0.072	0.055	0.056	0.035	0.022	0.050	0.050

Table 5.32. Vehicle Sustainability Indicators for Energy, Economy and Users (VMT)

Sustainability Category	Objectives	Indicators	Code	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Energy	Minimize energy consumption	Manufacturing energy	-	*Mjoule/VMT*	0.712	0.727	0.824	0.820	0.762	1.134	1.152	3.512	6.963	0.712	0.727
		Fueling energy	-	*Mjoule/VMT*	1.447	0.633	1.449	2.270	0.627	2.025	1.787	5.016	3.912	1.447	0.633
		Operation energy	-	*Mjoule/VMT*	5.816	3.011	2.181	1.711	4.118	9.289	7.536	38.062	30.005	5.959	3.172
		Maintenance energy	-	*Mjoule/VMT*	0.282	0.268	0.186	0.186	0.258	0.345	0.342	2.058	2.140	0.264	0.264
Economy	Reduce cost requirements	Manufacturing cost	-	*$/VMT*	0.168	0.181	0.268	0.185	0.216	0.191	0.246	0.579	0.996	0.559	0.602
		Operate (user costs)	-	*$/VMT*	0.264	0.183	0.214	0.183	0.227	0.407	0.319	0.367	0.376	1.266	1.266
		Maintenance cost	-	*$/VMT*	0.055	0.053	0.032	0.032	0.053	0.064	0.064	0.460	0.460	0.055	0.055
	Minimize governmental support	Subsidy	-	*$/VMT*	0.000	0.000	0.044	0.044	0.044	0.000	0.000	2.847	2.847	0.000	0.000
	Minimize parking requirements	Parking cost	-	$/month	161.6	161.6	0.0	0.0	0.0	161.6	161.6	0.0	0.0	0.0	0.0
User	Maximize transportation performance	Global availability	-	% of time not available for user's usage based on 24h	0.03%	0.02%	0.05%	9.61%	1.45%	0.03%	0.03%	20.83%	20.83%	0.05%	0.04%
		Reasonable availability	-	% of time not available for user's usage based on 19h	0.04%	0.03%	0.06%	3.47%	0.04%	0.04%	0.04%	0.00%	0.00%	0.06%	0.05%
	Maximize user comfort	Passenger space	+	*cu.ft/passenger*	20.3	18.7	25.2	18.4	23.0	21.7	30.3	33.1	29.1	20.3	18.7
		Goods carrying (cargo) space	+	*cu.ft/passenger*	3.00	4.32	3.28	2.44	2.65	18.47	4.20	1.85	1.85	3.00	4.32
		Leg room front	+	*inches*	41.7	42.5	41.9	42.1	42.0	41.4	40.6	27.0	27.0	41.7	42.5
	Maximize user confidence	Locations for fueling/charging	+	*Number of stations in operation*	121,446	121,446	58	626	121,446	121,446	121,446	NA	NA	121,446	121,446

Table 5.33. Vehicle Sustainability Indicators for Environment and Technology (PMT)

Sustainability Category	Objectives	Indicators	Code +/-	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Environment	Minimize global warming	CO_2 (w/ C in VOC & CO)	-	*grams/ PMT*	541	289	253	340	382	777	550	326	126	137	74
		CH_4	-	*grams/PMT*	0.75	0.45	0.78	0.55	0.46	1.12	0.78	0.27	0.10	0.21	0.14
		N_2O	-	*grams/PMT*	0.02	0.02	0.00	0.01	0.02	0.02	0.02	0.00	0.00	0.00	0.00
		GHGs	-	*grams/PMT*	566	305	273	356	399	813	576	339	133	144	79
	Minimize air pollution	VOC	-	*grams/PMT*	0.93	0.84	0.07	0.07	0.83	1.71	1.14	0.22	0.13	0.24	0.21
		CO	-	*grams/PMT*	6.93	6.88	0.41	0.42	6.81	11.63	6.35	0.90	0.51	1.75	1.74
		NO_x	-	*grams/PMT*	0.89	0.76	0.25	0.41	0.75	1.58	0.41	1.04	0.47	0.23	0.20
		PM_{10}	-	*grams/PMT*	0.18	0.15	0.18	0.48	0.14	0.27	0.20	0.07	0.04	0.05	0.04
		SO_x	-	*grams/PMT*	0.32	0.34	0.37	0.96	0.40	0.48	0.34	0.16	0.10	0.09	0.10
	Minimize noise	Noise	-	*dB*	61	57	57	57	57	69	64	78	78	61	57
Technology	Maximize lifetime service	Vehicle lifetime	+	*years*	10.6	10.6	15	15	15	9.6	9.6	12	12	2	2
	Maximize used resources	Capacity	+	*percentage*	100%	100%	80%	100%	80%	100%	100%	92%	99%	100%	100%
	Minimize time losses	Fuel frequency	-	*mins/PMT*	0.013	0.009	0.019	0.024	0.014	0.014	0.011	NA	NA	0.003	0.002
		Maintenance freq.	-	*mins/PMT*	0.019	0.017	0.007	0.006	0.012	0.022	0.017	0.003	0.001	0.013	0.010
	Minimize land consumption	Vehicle storage	-	*m^2/passenger*	7.6	6.8	7.8	6.9	6.7	9.8	7.1	3.0	2.0	1.9	1.7
	Maximize vehicle performance	Engine power	+	*lb.ft./lb*	0.050	0.050	0.053	0.059	0.072	0.055	0.056	0.035	0.022	0.050	0.050

Table 5.34. Vehicle Sustainability Indicators for Energy, Economy and Users (PMT)

Sustainability Category	Objectives	Indicators	Code +/-	Units	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Energy	Minimize energy consumption	Manufacturing energy	-	*Mjoule/PMT*	0.622	0.634	0.719	0.716	0.665	1.029	0.820	0.335	0.291	0.155	0.159
		Fueling energy	-	*Mjoule/PMT*	1.263	0.552	1.265	1.981	0.547	1.839	1.272	0.478	0.164	0.316	0.138
		Operation energy	-	*Mjoule/PMT*	5.076	2.627	1.904	1.493	3.594	8.433	5.365	3.625	1.255	1.300	0.692
		Maintenance energy	-	*Mjoule/PMT*	0.246	0.234	0.162	0.162	0.225	0.314	0.243	0.196	0.090	0.058	0.058
Economy	Reduce cost requirements	Manufacturing cost	-	*$/PMT*	0.147	0.158	0.234	0.162	0.189	0.173	0.175	0.055	0.042	0.122	0.131
		Operate (user costs)	-	*$/PMT*	0.231	0.160	0.187	0.159	0.198	0.369	0.227	0.367	0.376	0.276	0.276
		Maintenance cost	-	*$/PMT*	0.048	0.046	0.027	0.027	0.046	0.058	0.046	0.044	0.019	0.012	0.012
	Minimize governmental support	Subsidy	-	*$/PMT*	0.000	0.000	0.039	0.039	0.039	0.000	0.000	0.271	0.119	0.000	0.000
	Minimize parking requirements	Parking cost	-	$/pass.	141.0	141.0	0.0	0.0	0.0	146.7	115.0	0.0	0.0	0.0	0.0
User	Maximize transportation performance	Global availability	-	% of time not available for user's usage based on 24h	0.03%	0.02%	0.05%	9.61%	1.45%	0.03%	0.03%	20.83%	20.83%	0.05%	0.04%
		Reasonable availability	-	% of time not available for user's usage based on 19h	0.04%	0.03%	0.06%	3.47%	0.04%	0.04%	0.04%	0.00%	0.00%	0.06%	0.05%
	Maximize user comfort	Passenger space	+	*cu.ft/passenger*	20.3	18.7	25.2	18.4	23.0	21.7	30.3	33.1	29.1	20.3	18.7
		Goods carrying (cargo) space	+	*cu.ft/passenger*	3.00	4.32	3.28	2.44	2.65	18.47	4.20	1.85	1.85	3.00	4.32
		Leg room front	+	*inches*	41.7	42.5	41.9	42.1	42.0	41.4	40.6	27.0	27.0	41.7	42.5
	Maximize user confidence	Locations for fueling/charging	+	*Number of stations in operation*	121,446	121,446	58	626	121,446	121,446	121,446	NA	NA	121,446	121,446

Energy requirements for alternative fuel vehicle operation are significantly lower due to improved fuel efficiencies they have in relation to the gasoline powered vehicles. Table 5.35 shows the ranking of all vehicles per VMT and PMT. The vehicle rankings for energy consumption are similar with the vehicle ranking of GHG emissions of each vehicle over their lifetime. This reveals the relationship that exists between energy consumption and GHGs – mainly CO_2 – as energy sources are mainly non-renewable energy sources and they embrace CO_2 emissions.

Moreover, from vehicle rankings based on their energy consumption and GHGs in Tables 5.35 and 5.36 respectively, the important role of policies can be seen on vehicle occupancy and how these may shift an environmental unsustainable transportation mode to a sustainable one. SO_x and PM_{10} emissions are higher for an EV compared with all other vehicles, mostly due to electricity production and electricity feedstock, respectively.

Table 5.35. Vehicle Rankings per Energy Consumption

		ICEV	HEV	FCV	EV	PHEV	GPT	GSUV	DB	BRT	CS	CS
		Camry	Prius	Clarity	Leaf	Volt	F-150	Explorer	New flyer	New flyer	Camry	Prius
Energy	*Mj/VMT*	6	1	2	4	5	9	8	11	10	7	3
Energy	*Mj/PMT*	9	4	5	6	8	11	10	7	2	3	1

Table 5.36. Vehicle Rankings per GHG Emissions

		ICEV	HEV	FCV	EV	PHEV	GPT	GSUV	DB	BRT	CS	CS
		Camry	Prius	Clarity	Leaf	Volt	F-150	Explorer	New flyer	New flyer	Camry	Prius
GHGs	*grams/ VMT*	6	2	1	4	5	9	8	11	10	7	3
GHGs	*grams / PMT*	9	5	4	7	8	11	10	6	2	3	1

5.7. Sustainability Index

Due to the multidisciplinary character of sustainability, integration of sustainability indicators, into summary indices becomes a sensitive task that has to ensure that 1) the final result is understandable to decision makers and stakeholders, and 2) it has included all the sustainability indicators considered.

The proposed sustainability indicators are first separated into indicators with positive (+) impact, and indicators with negative (-) impact. Aggregation of indicators into a single sustainability dimension index per vehicle type, since indicators are expressed in different units, can be done by normalizing the value of each indicator for each vehicle type by using equations 5.11a and 5.11b and then combining these normalized values by assigning weights (Krajnc and Glavic 2005.)

$$N_{ij}^{+} = \frac{I_{ij}^{+} - I_{min,j}^{+}}{I_{max,j}^{+} - I_{min,j}^{+}} \quad (a) \qquad N_{ij}^{-} = \frac{I_{min,j}^{-} - I_{ij}^{-}}{I_{min,j}^{-} - I_{max,j}^{-}} \quad (b) \qquad (5.11)$$

Where N_{ij}^{+} is the normalized indicator with positive impact achieved by the *ith* alternative with respect to the *jth* indicator of sustainability. I_{ij}^{+} is the indicator value achieved by the *ith* alternative when evaluated based on the *jth* indicator, $I_{min,j}^{+}$ is the indicator with the worst value achieved by the *jth* indicator of sustainability and $I_{max,j}^{+}$ is the optimum value of *jth* indicator of sustainability obtained.

The normalized values are dimensionless and range from 0 to 1; therefore the greater the absolute value of the normalized indicator, the more sustainable it is. Hence, on a relative scale, the most sustainable vector for each vehicle type is $\mathrm{I}_{\mathrm{max,}} = (1, \ldots 1)$ and the least sustainable vector is $I_{min} = (0, \ldots 0)$ where its components equal the number of the sustainability dimensions.

Aggregation of normalized indicators for each sustainability dimension, and into overall sustainability indices per vehicle type is performed by using the weighted sum method (WSM) (Yoon and Hwang 1995.) The value of alternative A_i with assigned weight w_j for each indicator j can be expressed mathematically as:

$$V_i = \sum_{j=1}^{n} w_j N_{ij} \qquad\qquad i = 1, \ldots, m \qquad (5.\ 12)$$

In this analysis equal weights were assigned to each indicator and sustainability dimension. Tables 5.37 to 5.41 present the normalized values for all indicators, the sustainability dimension index and the overall sustainability index per vehicle type.

The sustainability dimension and overall sustainability index for each vehicle is used to compare the 11 vehicle types. When results are weighted by PMT, the overall sustainability indices indicate that the most sustainable vehicles are the CS and the BRT system. Non private vehicles play a role on sustainability because more passenger trips take place with a single vehicle. CS and BRT obtain the highest scores compared with all other vehicles in four out of the five sustainability dimensions. CS with a HEV is ranked as the “best” alternative for Environment and Energy, CS with an ICEV for Economy and BRT for Technology. The Environment and Energy results for those three types of public vehicles and their differences with private passengers reveal the significant differences in performance. On the contrary, Technology and Economy present more comparable results between all urban vehicles, which reveals that if a user or an agency is not particularly sensitive to issues related to environment and energy, then it is very probable to choose a vehicle that satisfies mostly other needs. The results for Users reveal that the vehicles that provide those needs to transportation users are the GPT and the GSUV. The two vehicles that obtained the worst ranking result in Environment and Energy. The result justifies the high rate of GPT and GSUV utilization in metropolitan areas where no policies are applied to restrict such vehicles.

Looking at private vehicles, the most promising technologies for Environment, Technology, Energy and Economy were found to be the HEV, the FCV and the EV. The EV achieves the maximum economic sustainability score after the CS program because of the low maintenance and low fuel cost related to the rest of the vehicles that use gasoline or hydrogen as basic fuel. In Technology, EV comes first due to the low maintenance frequency, the engine performance and the assigned long lifetime duration resulting from improved batteries. EV has the potential to score higher in this dimension if the charging infrastructure or the battery range advances to minimize time losses. Although EV performs relatively well, its overall sustainability index is obscured by the indicator "reasonable availability," which contributes significantly to its final ranking. Improvements in battery range performance and speed of charging will make EVs more reliable and thus more competitive.

The FCV comes first in Environment with a significant difference from all other passenger cars, and it even outreaches DB environmental performance, which is a public vehicle. Its SDI is higher by 25% compared with the second better passenger car for the dimension Environment. Although the importance of policies related to vehicle occupancy was shown from the results that were achieved by public vehicles, FCV's results for Environment shows that utilization of alternative technologies combined with occupancy related policies have the potential to bring the desirable outcome and achieve sustainability objectives and goals much faster. Those alternative technologies can be used in passenger vehicles and be combined with policies that promote carpooling, or/and in public vehicles to further improve their performance.

The HEV was found to score first in Energy, with a small difference from FCV and PHEV mostly due to the improved performance that demonstrates in manufacturing and fueling energy requirements when compared with alternative fuel vehicles including the FCV and PHEV. The main reasons for this result are the advanced materials used for battery manufacturing and the increased utilization of more energy demanding materials in terms of production during the vehicle manufacturing process for FCV and PHEV. Additionally, hydrogen and electricity production for FCV and PHEV respectively, resulted in higher energy requirements than gasoline production for HEV. Accounting for upstream emissions and energy requirements for alternative fuel vehicles, including FCV, PHEV and EV, versus operation only vehicle emissions and energy requirements becomes an important parameter in vehicle assessment. Upstream emissions from, and energy requirements for vehicle fuel production depend on the electricity mix used for every community, and therefore they may vary significantly for different geographical areas. Consideration of these parameters may play a significant role in future if the majority of the vehicles embrace alternative fuel based technologies.

The “optimum” sustainability performance assigned to the vehicle that obtained the highest sustainability index score is the “relative optimum” rather than the “absolute optimum” sustainability performance because it is the result of the comparison between the 11 alternative vehicles.

In order to measure the attainment of sustainability for each vehicle, the Attainment Sustainability Ratio (ASR) for each vehicle is estimated. First the maximum index per sustainability dimension is considered. Then the average of these indices is estimated (i.e., equal weights are assigned to each sustainability dimension.) The ASR for each vehicle type is defined as the ratio of the overall sustainability index for each vehicle to the average of maximum sustainability indices per dimension. ASR is expressed as a percentage and it is shown in Table 5.42 for each vehicle type together with vehicle rankings.

The four first places are occupied by the vehicles that are used by the public, the CS-HEV, the CS-ICEV, the BRT and the DB. The CS program with a HEV attained the highest percentage of sustainability with 95%; the CS program with ICEV came second with 92% of sustainability attainment. The BRT, which was ranked third, attained sustainability by 87% (i.e., 91% of CS' value) and the DB 71% (i.e., 75% of CS' value.)

Private passenger vehicles were ranked in order of highest to lowest score, with FCV, HEV, PHEV, EV, GSUV, ICEV and GPT achieving 69.7%, 67.2%, 66.8%, 64.5%, 56.7%, 55.2%, and 32.3%, respectively of the possible maximum overall sustainability.

The proposed indicators are integrated into a tool that is able to appraise transportation modes in a sustainability context and supports the decision making process for existing or new transportation modes. Given the fleet percentages of network or part of the network, the sustainability performance can be estimated as in this chapter. Network specific parameters and project-specific parameters can be used.

Table 5.37. Normalized Values for Environment

Sustainability Category	Weight	Objectives	Indicators	Weights	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Environment	0.2	Minimize global warming	CO_2 (w/ C in VOC & CO)	*0.10*	0.336	0.695	0.746	0.621	0.563	0.000	0.323	0.642	0.926	0.911	1.000
			CH_4	*0.10*	0.365	0.657	0.338	0.563	0.651	0.000	0.335	0.837	1.000	0.893	0.964
			N_2O	*0.10*	0.182	0.326	0.890	0.764	0.320	0.000	0.264	0.949	1.000	0.815	0.850
			GHGs	*0.10*	0.336	0.692	0.735	0.623	0.565	0.000	0.324	0.646	0.927	0.912	1.000
		Minimize air pollution	VOC	*0.10*	0.472	0.530	1.000	0.998	0.537	0.000	0.346	0.908	0.965	0.898	0.912
			CO	*0.10*	0.418	0.423	1.000	0.999	0.430	0.000	0.471	0.956	0.991	0.880	0.881
			NO_x	*0.10*	0.500	0.593	0.964	0.848	0.599	0.000	0.846	0.390	0.801	0.977	1.000
			PM_{10}	*0.10*	0.680	0.747	0.682	0.000	0.751	0.467	0.636	0.930	1.000	0.976	0.992
			SO_x	*0.10*	0.730	0.706	0.677	0.000	0.642	0.551	0.713	0.916	0.991	1.000	0.993
		Minimize noise	Noise	*0.10*	0.810	1.000	1.000	1.000	1.000	0.429	0.667	0.000	0.000	0.810	1.000
	Environment sustainability index per vehicle type				**0.483**	**0.637**	**0.803**	**0.642**	**0.606**	**0.145**	**0.492**	**0.717**	**0.860**	**0.907**	**0.959**

Table 5.38. Normalized Values for Technology

Sustainability Category	Weight	Objectives	Indicators	Weights	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Technology	0.2	Maximize lifetime service	Vehicle lifetime	*0.17*	0.662	0.662	1.000	1.000	1.000	0.585	0.585	0.769	0.769	0.000	0.000
		Maximize capacity of vehicle in the unit of time	Capacity	*0.17*	1.000	1.000	0.000	1.000	0.000	1.000	1.000	0.620	0.957	1.000	1.000
		Minimize time losses	Fuel frequency	*0.17*	0.516	0.685	0.256	0.000	0.449	0.466	0.604	1.000	1.000	0.958	1.000
			Maintenance freq.	*0.17*	0.138	0.222	0.736	0.766	0.468	0.000	0.229	0.920	1.000	0.433	0.573
		Minimize land consumption	Vehicle storage	*0.17*	0.271	0.375	0.252	0.366	0.380	0.000	0.332	0.839	0.957	0.974	1.000
		Maximize veh. performance	Engine power	*0.17*	0.564	0.560	0.609	0.738	1.000	0.656	0.672	0.245	0.000	0.564	0.560
Technology sustainability index per vehicle type					**0.450**	**0.500**	**0.408**	**0.553**	**0.471**	**0.387**	**0.489**	**0.628**	**0.669**	**0.561**	**0.590**

Table 5.39. Normalized Values for Energy

Sustainability Category	Weight	Objectives	Indicators	Weights	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Energy	0.2	Minimize energy consumption	Manufacturing energy	*0.25*	0.466	0.452	0.355	0.358	0.416	0.000	0.239	0.795	0.844	1.000	0.996
			Fueling energy	*0.25*	0.390	0.775	0.389	0.000	0.778	0.077	0.385	0.816	0.986	0.904	1.000
			Operation energy	*0.25*	0.434	0.750	0.843	0.897	0.625	0.000	0.396	0.621	0.927	0.921	1.000
			Maintenance energy	*0.25*	0.263	0.312	0.592	0.592	0.344	0.000	0.274	0.460	0.875	1.000	1.000
	Energy sustainability index per vehicle type				**0.388**	**0.572**	**0.545**	**0.462**	**0.541**	**0.019**	**0.324**	**0.673**	**0.908**	**0.956**	**0.999**

Table 5.40. Normalized Values for Economy

Sustainability Category	Weight	Objectives	Indicators	Weights	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
Economy	0.2	Reduce cost requirements	Manufacturing cost	*0.20*	0.454	0.396	0.000	0.376	0.235	0.316	0.304	0.930	1.000	0.583	0.534
			Operate (user costs)	*0.20*	0.671	0.997	0.874	1.000	0.823	0.032	0.686	0.043	0.000	0.461	0.461
			Maintenance cost	*0.20*	0.219	0.263	0.664	0.664	0.264	0.000	0.272	0.310	0.843	1.000	1.000
		Minimize governmental support	Subsidy	*0.20*	1.000	1.000	0.858	0.858	0.858	1.000	1.000	0.000	0.561	1.000	1.000
		Minimize parking requirements	Parking cost	*0.20*	0.039	0.039	1.000	1.000	1.000	0.000	0.216	1.000	1.000	1.000	1.000
	Economy sustainability index per vehicle type				**0.341**	**0.385**	**0.485**	**0.557**	**0.454**	**0.193**	**0.354**	**0.326**	**0.486**	**0.578**	**0.561**

Table 5.41. Normalized Values for Users

Sustainability Category	Weight	Objectives	Indicators	Weights	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
User	0.2	Maximize transportation performance	Global availability	*0.17*	1.000	1.000	0.999	0.539	0.932	0.999	0.999	0.000	0.000	0.999	0.999
			Reasonable availability	*0.17*	0.988	0.992	0.983	0.000	0.987	0.988	0.988	1.000	1.000	0.982	0.987
		Maximize user comfort	Passenger space	*0.17*	0.128	0.023	0.464	0.000	0.314	0.227	0.814	1.000	0.732	0.128	0.023
			Goods carrying (cargo) space	*0.17*	0.069	0.149	0.086	0.036	0.048	1.000	0.141	0.000	0.000	0.069	0.149
			Leg room front	*0.17*	0.948	1.000	0.961	0.974	0.968	0.929	0.877	0.000	0.000	0.948	1.000
		Maximize user confidence	Fueling opportunities	*0.17*	1.000	1.000	0.000	0.005	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	User sustainability index per vehicle type				**0.344**	**0.347**	**0.291**	**0.129**	**0.354**	**0.429**	**0.402**	**0.250**	**0.228**	**0.344**	**0.347**
	Overall sustainability per vehicle type				**40.1**	**48.8**	**50.6**	**46.8**	**48.5**	**23.4**	**41.2**	**51.9**	**63.0**	**66.9**	**69.3**

Table 5.42. Vehicle Attainment Sustainability Ratio and Rankings

	ICEV Camry	HEV Prius	FCV Clarity	EV Leaf	PHEV Volt	GPT F-150	GSUV Explorer	DB New flyer	BRT New flyer	CS Camry	CS Prius
ASR % (VMT)	84.3%	90.0%	90.5%	86.3%	91.5%	77.5%	81.5%	38.7%	34.5%	79.8%	85.5%
ASR % (PMT)	55.2%	67.2%	69.7%	64.5%	66.8%	32.3%	56.7%	71.4%	86.7%	92.1%	95.4%
Rankings (VMT)	**6**	**3**	**2**	**4**	**1**	**9**	**7**	**10**	**11**	**8**	**5**
Ranking (PMT)	**10**	**6**	**5**	**8**	**7**	**11**	**9**	**4**	**3**	**2**	**1**

CHAPTER 6

URBAN TRANSPORTATION SUSTAINABILITY: A CASE STUDY OF THREE METROPOLITAN AREAS

Transport sustainability indicators that measure impacts on mobility, safety and environment are applied mainly to the operation of the transportation system and other major components of sustainable transportation are omitted, as it was reviewed in Chapter 2. Incorporation of sustainability into transportation planning will assist agencies to evaluate new transportation modes that are proposed for introduction in a network. However, consideration exclusively of personal vehicles or all modes present on a section of a network by using aggregated measures, such as total emissions to measure impact on environment, limits sustainability role and may lead to ineffective transportation policies.

The accelerated development and introduction of vehicles with alternative propulsion systems compel a detailed breakdown of vehicle components and characteristics for the proper understanding of their performance and impacts over their entire life cycle. Disaggregation per vehicle type (i.e., consider vehicle operational and functional characteristics) in a transportation network and life cycle sustainability assessment for each type has the potential to lead to more accurate planning and policy making. Sustainability indicators that differ greatly for different vehicle types and are important for transportation planning may be critical for long term sustainability of the transportation system, and therefore they should be considered.

This chapter explores the application of a life cycle sustainability tool (LCST) in transportation planning by using the results for different vehicle types from Chapter 5, and transportation data from three metropolitan areas. In the form of a case study, the results are aggregated to assess the transport sustainability of three metropolitan areas by taking into account their transportation characteristics. The first part of this chapter presents the methodology used, the data required for implementing the LCST and the assumptions considered for the assessment of the metropolitan areas of Atlanta, Chicago and OPTIMUS. The second part outlines the results from the assessment together with a discussion of how the developed tool may support decision making in transportation.

6.1. Methodology and Data Sources

The objective of this exercise was to explore the application of the life cycle sustainability framework (LCSF) in networks with different transportation and demographic characteristics and to develop a LCST that can reveal the tradeoffs that occur from transportation policies and planning.

Atlanta, Chicago, and a hypothetical metropolitan area called OPTIMUS (OPtimal Transportation Indicators for Modeling Urban Sustainability) are used in this transportation sustainability assessment. OPTIMUS combines characteristics from U.S. metropolitan areas that are likely to increase its sustainability performance. Their data are collected from several literature sources as described below.

Regional household travel surveys conducted by Atlanta Regional Commission and Chicago Metropolitan Agency for Planning are used to extract transportation data for Atlanta and Chicago, respectively. The household travel surveys collect information on work and non-work travel behavior. Their objective is to produce data that could be used to develop and calibrate travel demand models for use in travel forecasting, land use planning, and air quality planning. These include trip generation, trip distribution, and modal choice as well as data on transit use and neighborhood preferences.

The assessment of the three metropolitan areas with different populations and transportation characteristics is performed by weighting the sustainability indicators per area passenger miles traveled (PMT) to eliminate inconsistencies due to different population sizes. If this is not applicable to a sustainability indicator, then its average value is considered.

In order to combine sustainability indicators into a single dimensionless index, the indicators had to be normalized to eliminate computational issues since they have different units and vastly different ranges and magnitudes. Indicators were normalized by equation 6.1

$$N_{ij} = \frac{I_{ij}}{I^*} \tag{6.1}$$

Where N_{ij} is the is the normalized indicator achieved by the *ith* alternative with respect to the *jth* indicator of sustainability, I_{ij} is the indicator value achieved by the *ith* alternative when evaluated based on the *jth* indicator, and I^* is the optimum value of the *jth* indicator. The optimum value is the maximum for indicators with positive impact and the minimum for indicators with negative impact.

The developed LCST for the assessment of urban transportation sustainability is a spreadsheet based application that requires a certain amount of input data for each metropolitan area including vehicle parking cost, vehicle trip share, ownership ratio, fuel price and so on. The complete input list is presented in section 6.1.1.

The developed LCST is supported by a visual interface (i.e., a normal pentagon) that illustrates sustainability dimension indices for each metropolitan area. This enables decision makers and policy analysts to explore variations in sustainability performance.

6.1.1. Atlanta and Chicago

The specific metropolitan areas of Atlanta and Chicago were selected due to the availability of recent trip data. Data for Atlanta and Chicago metropolitan areas is extracted and processed from the Household Travel Survey conducted in each region (ARC 2003, CMAP 2008.)

The Atlanta Household Travel Survey sampled 8,069 households in thirteen county nonattainment areas. A total of 12,184 households were recruited to participate in the study and 8,069 households (66%) completed the travel data. The 8,069 households represent 21,323 persons and 14,449 vehicles. The Chicago Regional Household Travel Inventory is a comprehensive study of the demographic and travel behavior characteristics of residents in the greater Chicago area. In total, 25,845 households were recruited to participate in the study and 14,390 provided travel data.

The data from the household trip surveys and other literature sources underpin the present analysis for the sustainability assessment of metropolitan areas. For metropolitan area data needed but not provided directly by the trip surveys, assumptions made to estimate and to complete the required datasets. The list of data input for each metropolitan area together with the corresponding data sources are presented below and their corresponding values are presented in Table 6.1.

- Vehicle fuel price (AAA 2007, DOE 2009.)
- Vehicle parking cost (Colliers International 2010.)

- Vehicle ownership ratio – It is required only when the number of vehicles per metropolitan area is not available, thus it was not necessary for Atlanta and Chicago.
- Number of passengers per metropolitan area (ARC 2003, CMAP 2008.)
- Mode split by trip – It is provided directly from survey reports for basic transportation vehicles (e.g., passenger cars, public transit, taxis, walk etc.). For different passenger car types (e.g., ICEV, HEV, EV, etc.) it is assumed that their share of trips are similar to the passenger car share which is estimated from data provided by the survey report and described below (ARC 2003, CMAP 2008.)
- Average miles per trip per vehicle type – It is provided directly from survey reports or it is estimated by dividing the PMT by the passenger trips for each vehicle type (ARC 2003, CMAP 2008.)
- Cost to purchase vehicle (Edmunds 2002, CLG 2008.)
- Public transit fare (APTA 2009, MARTA 2011, CTA 2011.)
- Insurance cost per vehicle type (Insurance Information Institute 2010). The insurance cost (2008$) for the ICEV is estimated and the costs for all other vehicles are estimated proportional to vehicles' weight. (This criterion needs improvement in a future revision.) Insurance cost for CS is estimated as the average of 2002 insurance cost per vehicle per year for CS programs (TCRP 2002.)
- Number of fueling or charging stations available per metropolitan area (U.S. DOE 2011a, Gas Station Directory 2011.)

- Vehicle occupancy per vehicle type – The estimated average vehicle occupancy ratios for all metropolitan areas are described in section 6.1.3.

Table 6.1. Input Parameters for Metropolitan Areas

Data Input	Units	Atlanta	Chicago	OPTIMUS
Gasoline price (May 2011)	*$/gallon*	3.78	4.22	3.56
Diesel price (May 2011)	*$/gallon*	3.97	4.56	3.83
Electricity price (May 2011)	*$/kWh*	0.11	0.15	0.08
Vehicle parking cost (2010)	*$/month*	93	320	129
Vehicle ownership ratio	*veh./capita*	0.64	0.66	0.65
Number of passengers	*passengers*	3,240,601	7,396,287	705,786
Trips per passenger per bus	*pass./trip*	10.4	9.8	10.5
Mode split by trip – ICEV	*%trips/veh.type*	50.4%	40.8%	40.0%
Mode split by trip – HEV	*%trips/veh.type*	1.7%	1.2%	3.0%
Mode split by trip – FCV	*%trips/veh.type*	0.0%	0.0%	0.01%
Mode split by trip – EV	*%trips/veh.type*	0.2%	0.1%	0.8%
Mode split by trip – PHEV	*%trips/veh.type*	0.0%	0.0%	0.4%
Mode split by trip – GPT	*%trips/veh.type*	11.3%	8.8%	5.0%
Mode split by trip – GSUV	*%trips/veh.type*	10.9%	15.2%	10.0%
Mode split by trip – DB	*%trips/veh.type*	1.4%	3.3%	4.0%
Mode split by trip – BRT	*%trips/veh.type*	0.0%	0.0%	0.4%
Average miles per trip per passenger car	*miles/trip*	10	4.8	10
Average miles per trip per bus	*miles/trip*	8.4	2.7	3.9
Average miles per trip per CS	*miles/trip*	-	-	5.5
Insurance cost per base vehicle	*$/year*	943	943	519
Number of available gasoline stations	*stations/mil.cap.*	96	112	235
Number of available electric stations	*stations/mil.cap.*	19	25	208
Number of available hydrogen stations	*stations/mil.cap.*	0	1	5

In order to estimate HEV shares of total vehicle share in Atlanta, the annual sales rate for Atlanta is used. HEV sales in Atlanta accounted for 1.41% and 0.85% of national HEV sales in 2006 and 2009, respectively. The average annual HEV sales for Atlanta are estimated to account for 1.13% of the national sales. The number of HEVs in Atlanta is estimated by multiplying the total number of HEVs in U.S with Atlanta's HEV sales rate. The national HEV sales since 1999 are 1,888,971 vehicles and it is estimated that 21,335 HEVs are in Atlanta. The 21,335 HEVs account for 1.7% of Atlanta's passenger cars (Hybrid Cars 2006, 2009 and U.S. DOE 2011b.)

Applying the same procedure for Chicago, it is estimated that Chicago's average HEV sales account for 2.42% of the national sales. It is estimated that there are approximately 46,000 HEV in Chicago that account for 1.2% of the passenger cars (Hybrid Cars 2006, 2009 and U.S. DOE 2011b.)

6.1.2. OPTIMUS Metropolitan Area

OPTIMUS adopts values from other U.S. metropolitan areas that have the potential to boost transportation sustainability. Sustainability is not a measureable parameter, like the "level of service", therefore absolute values that could describe an alternative as sustainable, unsustainable or sustainable to a degree do not exist. Sustainability assessment may be performed by comparing two or more alternatives in order to estimate their relative sustainability performance and choose the one that satisfies stated goals of environmental, social or economic performance. Another approach is to consider OPTIMUS as a hypothetical metropolitan area that can achieve a high degree of sustainability on all stated dimensions. We refer to a high degree of sustainability as an approximation of the "maximum achievable" sustainability which is based on characteristics of other metropolitan areas under current conditions. At the present time, for many criteria, the theoretical maximum and minimum values are not known. However, one can evaluate for "maximum sustainability" by setting negative criteria to 0 and positive criteria to 1. These values however may be too unrealistic to be useful. OPTIMUS enables one to:

- Express sustainability performance of a metropolitan area relative to a high (achievable) degree of sustainability. Comparison with maximum achievable sustainability levels could result in enhanced long term planning instead of setting goals that in the long term may prove to be poor or diverging from sustainability.
- Set a target point in sustainability performance for other metropolitan areas that are willing to adopt policies and practices for improving sustainability.

Adopting policies that reach OPTIMUS' sustainability performance may be difficult and simultaneous maximization of sustainability in all stated dimensions impossible. However, the existence of a target point can improve the planning process by adopting policies and practices that move each metropolitan area towards OPTIMUS. The adopted and estimated values assigned to OPTIMUS and the representative metropolitan areas for each value are described below.

- **Lowest fuel cost** – The minimum average cost of gasoline and diesel as of May 2011 was found to be 3.560 $/gallon and 3.834 $/gallon respectively in South Carolina (AAA 2011.) The rational of using the lowest vehicle operation costs in this exercise is the minimization of out of pocket costs for transportation users and the maximization of economic sustainability. Low user costs provide mobility options to users across all economic levels.
- **Lowest electricity cost** – The minimum average electricity cost for residential use as for May 2011 was found to be 0.0764 $/kWh in the State of North Dakota.

A list with the average retail prices of electricity to ultimate customers for residential sector by state is shown in Appendix E (EIA 2011.)

- **Lowest insurance cost** – Insurance cost of $519 (2008$.) is lowest. The insurance costs for the rest of the vehicles are estimated based on vehicle weights (Insurance Information Institute 2010.)
- **Average parking cost** – For the estimation of the average parking cost in the U.S. the ten highest and lowest metropolitan cities were excluded. The cost for the rest average $129.5 (2010$) and is approximately equal to the average parking cost of Columbus, OH and Tampa, FL (Colliers International 2010.) It is assumed that only 50% of users are paying for vehicle parking, for all three metropolitan areas. The average parking cost is considered instead of the lowest one due to high fluctuations in cost values between metropolitan areas. Lowest parking costs resulted in high differences between the normalized values of metropolitan areas when compared with each other, and they favored greatly small metropolitan areas with the lowest parking costs.
- **Average vehicle ownership ratio** – The number of vehicles per capita by state varies considerably. Wyoming has the highest number of vehicles per capita (1.14) and neighboring Colorado has the lowest (0.34). The average vehicle ownership ratio for the United States is 0.78. For OPTIMUS the national average rate is adjusted to represent an average for metropolitan areas. The adjustment ratio is estimated to be the average value of the differences between state and metropolitan vehicle ownership ratios for Georgia – Atlanta and Illinois – Chicago. The vehicle ownership ratio for Chicago is lower by 21% of the Illinois

ratio and for Atlanta is 12% lower than the Georgia ratio. For OPTIMUS the average ownership ratio is estimated to be 0.65 based on 16.5% reduction of the national ratio (U.S. DOE 2007, ARC 2003, CMAP 2008.)

- **Average metropolitan area size** – The United States Office of Management and Budget (OMB) defines a Metropolitan Statistical Area (MSA) as a core based statistical area having at least one urbanized area of 50,000 or more population, plus adjacent territory that has a high degree of social and economic integration with the core as measured by commuting ties. The OMB has defined 367 MSAs for the United States as of March 29, 2010 and the average size of MSA as counted by the United States Census 2010 is estimated (U.S Census Bureau 2010.) A list of all MSAs and their population is shown in Appendix E. OPTIMUS size was equal to 705,786 people
- **Average trips per passenger** – The average trips per passenger for OPTIMUS was based on the national average daily trips per person including trips taken by children younger than four years old, which is found to be 4.03 (FHWA 2004.)
- **Average miles per trip** – The average miles per trip are 10, 5.5, 3.9 and 4.6 for passenger cars, CS program, DB and BRT, respectively. It has been estimated that CS members drive an average of 47%-71% less after joining the program. The lower value of 47% is adopted in this case study (FHWA 2004, Cervero and Yuhsin 2003, APTA 2009, TCRP 2002.)
- **Maximum vehicle occupancy ratio** – The average maximum vehicle occupancy ratio is estimated to be 1.279 and it corresponds to the metropolitan area of

Honolulu. Vehicle occupancy estimations per vehicle type are very significant and are treated separately in section 6.1.3.

- **Maximum fueling/charging stations** – Refers to the maximum rate of fueling and charging station that are available in a metropolitan area per capita. Based on the results for all states, North Dakota comes first with 235 gas stations per million citizens. California has the highest number of charging and hydrogen stations per million citizens, equal to 208 and 5, respectively. Public and private stations are included for both types of stations, and does not include residential electric charging infrastructure as of May 2011 (U.S. DOE 2011a, Gas Station Directory 2011.) Based on population proportions it is estimated that 166, 147 and 4 gas, electric and hydrogen stations respectively will be available in OPTIMUS. A list with gas, electric and hydrogen stations per state is shown in Appendix E.
- **Optimal fleet mix –** It is based on forecasted fleet composition for 2015. The Center for Entrepreneurship and Technology (2009) estimated that HEVs and EVs will account for 3.0% and 1.1%, respectively of the light-vehicle fleet in 2015. For OPTIMUS it is assumed that HEVs will account for 3.0% of the trip shares. The 1.2% is shared between EV and PHEV based on their total sales proportion. Nissan Leaf, representative model for EV, has approximately 85% more sales than Chevrolet Volt, representative model for PHEV, from January to September 2011. The total and per month sales for each vehicle are shown in Table 6.2 (Autoblog Green 2011, MNN 2011.) Based on EV and PHEV sales proportion, it is estimated that EVs and PHEVs will account for 0.7% and 0.4% of the trip shares, respectively. FCVs in 2015 will approximately account in North

America for 0.005% of total vehicles based on Pike Research (Pike Research 2011.) For other vehicle types the trip shares were estimated to the nearest round towards the direction to improve overall sustainability. For example, for GPT the Atlanta and Chicago trip shares account for 13% and 9%, respectively; the OPTIMUS share is assumed to be 5%. GPTs are considered to reduce sustainability performance since their overall sustainability performance, as from Chapter 5, was estimated to be poor.

Table 6.2. EV and PHEV Sales in N.America from January to October 2011

	Chevrolet Volt	Nissan Leaf
January	321	87
February	281	67
March	608	298
April	493	573
May	481	1142
June	561	1708
July	125	931
August	302	1362
September	723	1031
Total	**3,895**	**7,199**

- **Highest public transit use** – Public transit refers to the high DB and BRT trip share observed for a metropolitan area in U.S. BRT is generally lumped with regular bus service shares in reports. Atlanta and Chicago bus utilization are 1.4% and 3.3%, respectively. The OPTIMUS bus share is assumed to be the nearest round, 4.0%. As mentioned in earlier chapter, BRT is usually modeled as light-rail. Light-rail trips accounted for 10.0% of bus trips from January to June 2011

(APTA 2011.) Based on these shares, the BRT trip ratio is estimated to be 0.4% or 10% of 4%.

- **Car Sharing** – CS program is a supplement of public transportation options in OPTIMUS. In communities where CS is available, users make an average of 3.34 trips per month using CS, which accounts for approximately 2.76% of person trips per month (TCRP 2005.) The same source states that despite rapid growth, CS accounts for just 0.03% of U.S. licensed drivers.

6.1.3. Vehicle Occupancy Rates

The average vehicle occupancy rate per vehicle type is required for accurate estimates of passenger travel (PMT.) Trip surveys do not provide occupancy rates for different passenger cars (i.e., ICEV, GSUV, GPT.) Due to data limitations, the occupancy rate has to be estimated first for states and then for metropolitan areas by using other data sources. Hawaii was found to have the higher vehicle occupancy rate, and it used for estimating OPTIMUS occupancy rate. In this part we estimate first the AVO for the state of Georgia, Illinois and Hawaii, and then for Atlanta, Chicago and OPTIMUS.

From Chapter 5 we have already estimated the metropolitan average vehicle occupancy (MAVO). In order to obtain the AVO for Atlanta, Chicago and OPTIMUS, the difference of MAVO and the states' AVO is added to the Georgia, Illinois and Hawaii average vehicle occupancy. The average occupancy for sedan, pickup truck and SUV is estimated by multiplying the AVO for each metropolitan area by the factor of 0.941, 0.904 and 1.404 (i.e., the ratio of sedan, pickup truck and SUV national occupancies to national average occupancy,) respectively. Results for each vehicle type are shown in Table 6.3.

All other parameters remain the same. The case study explores two cases. In the first one the nine vehicles included without the CS program and in the second case a CS program was considered. This is done to test the expandability of the LCSF with other mode choices.

Table 6.3. Vehicle Occupancy per Vehicle Type and Metropolitan Area

	Atlanta	Chicago	OPTIMUS
ICEV	1.158	1.139	1.204
GPT	1.113	1.095	1.157
SUV	1.420	1.396	1.475
Average	1.230	1.210	1.279

6.2. Results and Discussion

This section presents the results aggregated per sustainability indicator and metropolitan area. Aggregated indicator values are shown in Tables 6.4 and 6.5 together with their units, for Atlanta, Chicago and OPTIMUS. The indicators that reveal increased sustainability preferences in accordance with their increasing value are denoted with (+); whereas criteria with decreasing sustainability preference as their value increases are denoted with (-).Tables 6.4 and 6.5 present the aggregate indicator values per metropolitan area. Tables 6.6 and 6.7 show the normalized indicator values and provide a comprehensive comparison based on individual normalized indicators and sustainability indices.

The weighted sum model (WSM) methodology is used in this case study. It was described in Chapter 5 to develop a sustainability dimension index (SDI) and an overall sustainability index (OSI) for vehicles. The SDI can provide an initial estimate of an alternative's sustainability performance for the five dimensions by presenting their relative sustainability performance. This index provides an aggregated result and hides information on individual indicators that contribute (negatively or positively) to its estimation. However, the SDI provides a general evaluation index and distinguishes sustainability dimensions for an assessed alternative with inferior or superior performance compared to other alternatives.

For this research equal weights are assigned to aggregated normalized values and to sustainability dimensions to represent equal relative importance among them. Weight selection is a controversial issue because it exposes the analysis to a certain amount of subjectivity; however weights serve as an important tool to show the relative importance of each indicator as perceived by the decision maker (Zietsman 2006.) Future research is necessary to address the issue of weights for sustainability indicators and dimensions. A Delphi forecast, which embraces a panel of experts and their judgments, may be a more appropriate methodology for the real world application of the proposed sustainability assessment. Additionally, a sensitivity analysis can reveal how conclusions change based on the assigned weights per sustainability indicator and dimension. Figure 6.1 shows the specific steps that were taken to obtain the final OSI.

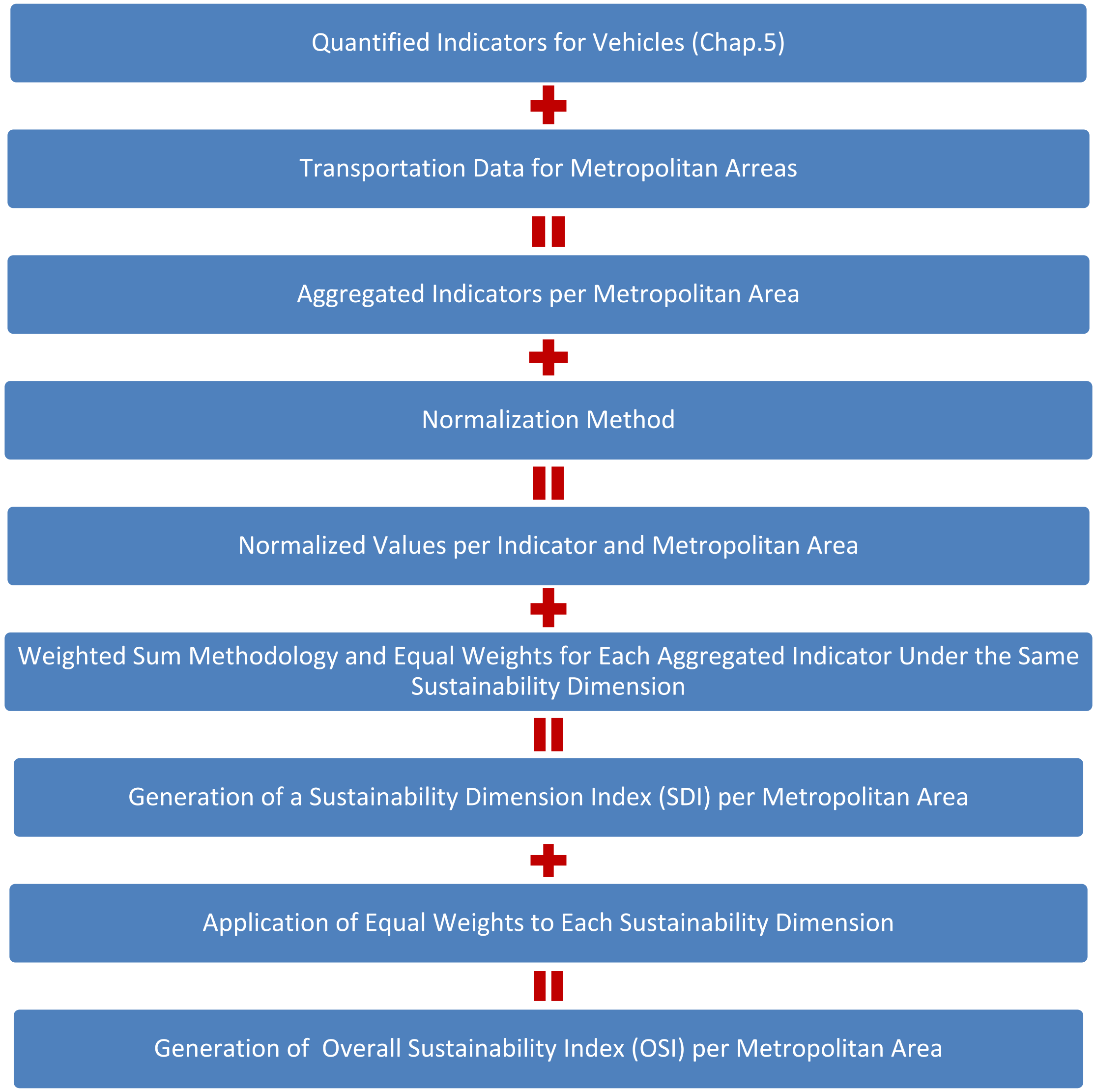

Figure 6.1. Actions to Obtain SDI and OSI per Metropolitan Area

Table 6.4. Aggregated Sustainability Indicators per Metropolitan Area (Part A)

Sustainability Dimension	Objectives	Indicators	Code +/-	Units	Atlanta	Chicago	OPTIMUS
Environment	Minimize global warming	CO_2 (w/ C in VOC & CO)	-	*grams/PMT*	596.6	595.5	518.9
		CH_4	-	*grams/PMT*	0.78	0.77	0.65
		N_2O	-	*grams/PMT*	0.02	0.02	0.02
		GHGs	-	*grams/PMT*	624.4	623.2	543.1
	Minimize air pollution	VOC	-	*grams/PMT*	1.12	1.12	0.96
		CO	-	*grams/PMT*	7.79	7.67	6.70
		NO_x	-	*grams/PMT*	0.95	0.92	0.82
		PM_{10}	-	*grams/PMT*	0.20	0.20	0.18
		SO_x	-	*grams/PMT*	0.37	0.36	0.33
	Minimize noise	Noise	-	*db*	63.9	63.9	63.2
Technology	Maximize lifetime service	Vehicle lifetime	+	*avg.veh.lifetime*	10.3	10.2	10.4
	Maximize capacity of vehicle in the unit of time	Capacity	+	*avg.capacity accomp.*	100.00%	100.00%	99.85%
	Minimize time losses	Fuel frequency	-	*avg.hours/pass.*	1.53	1.54	1.07
		Maintenance freq.	-	*avg.hours/pass.*	2.34	2.37	1.62
	Minimize land consumption	Vehicle storage	-	*Area/passenger*	5.06	5.12	3.51
	Maximize power	Engine power	+	*avg. lb.ft./lb*	0.052	0.052	0.052
Energy	Minimize energy consumption	Manufacturing energy	-	*kJ/PMT*	630	624	548
		Fueling energy	-	*kJ/PMT*	1,181	1,156	1,019
		Operation energy	-	*kJ/PMT*	4,772	4,687	4,031
		Maintenance energy	-	*kJ/PMT*	226	221	199

Table 6.5. Aggregated Sustainability Indicators per Metropolitan Area (Part B)

Sustainability Dimension	Objectives	Indicators	Code +/-	Units	Atlanta	Chicago	OPTIMUS
Economy	Reduce cost requirements	Manufacturing cost	-	*$/PMT*	19,167	19,405	17,767
		Operate (user costs)	-	*$/PMT*	0.302	0.335	0.225
		Maintenance cost	-	*$/PMT*	0.051	0.051	0.046
	Minimize governmental support	Subsidy	-	*$/PMT*	0.283	0.308	0.284
	Minimize parking requirements	Parking cost	-	*$/PMT*	0.0286	0.2129	0.0326
Users	Maximize transportation performance	Demand	+	*mode types with higher percentage share*	2	1	3
		Global availability	-	*avg. hours of down time or not operable per year expressed as an annual %*	0.06%	0.05%	0.18%
		Reasonable availability	-	*avg. hours of down time or not operable per year expressed as an annual %*	0.05%	0.04%	0.08%
	Maximize user comfort	Passenger space	+	*avg. cu.ft/passenger*	22.0	22.8	22.0
		Goods carrying (cargo) space	+	*avg. cu.ft/passenger*	5.6	5.4	4.6
		Leg room front	+	*avg. in inches*	41.50	41.42	41.52
	Maximize user comfort	Fueling opportunities	+	*avg. fuel stations/veh*	0.00019	0.00025	0.00117

Table 6.6. Normalized Sustainability Indicators per Metropolitan Area (Part A)

Sustainability Dimension	Objectives	Indicators	Code +/-	Units	Atlanta	Chicago	OPTIMUS
Environment	Minimize global warming	CO_2 (w/ C in VOC & CO)	-	*grams/PMT*	0.8698	0.8714	1.0000
		CH_4	-	*grams/PMT*	0.8333	0.8363	1.0000
		N_2O	-	*grams/PMT*	0.8790	0.8911	1.0000
		GHGs	-	*grams/PMT*	0.8699	0.8716	1.0000
	Minimize air pollution	VOC	-	*grams/PMT*	0.8535	0.8531	1.0000
		CO	-	*grams/PMT*	0.8604	0.8740	1.0000
		NO_x	-	*grams/PMT*	0.8683	0.8932	1.0000
		PM_{10}	-	*grams/PMT*	0.8872	0.8912	1.0000
		SO_x	-	*grams/PMT*	0.8929	0.8997	1.0000
	Minimize noise	Noise	-	*db*	0.9877	0.9885	1.0000
	Environment sustainability index per city				**0.8802**	**0.8870**	**1.0000**
Technology	Maximize lifetime service	Vehicle lifetime	+	*avg.veh.lifetime*	0.9882	0.9818	1.0000
	Maximize capacity of vehicle in the unit of time	Capacity	+	*avg.capacity accomp.*	1.0000	1.0000	0.9986
	Minimize time losses	Fuel frequency	-	*avg.hours/pass.*	0.7008	0.6967	1.0000
		Maintenance freq.	-	*avg.hours/pass.*	0.6955	0.6864	1.0000
	Minimize land consumption	Vehicle storage	-	*Area/passenger*	0.6933	0.6845	1.0000
	Maximize power	Engine power	+	*avg. lb.ft./lb*	0.9936	1.0000	0.9936
	Technology sustainability index per city				**0.8452**	**0.8416**	**0.9987**
Energy	Minimize energy consumption	Manufacturing energy	-	*kJ/PMT*	0.8695	0.8782	1.0000
		Fueling energy	-	*kJ/PMT*	0.8630	0.8815	1.0000
		Operation energy	-	*kJ/PMT*	0.8449	0.8601	1.0000
		Maintenance energy	-	*kJ/PMT*	0.8805	0.8995	1.0000
	Energy sustainability index per city				**0.8645**	**0.8798**	**1.0000**

Table 6.7. Normalized Sustainability Indicators per Metropolitan Area (Part B)

Sustainability Dimension	Objectives	Indicators	Code +/-	Units	Atlanta	Chicago	OPTIMUS
Economy	Reduce cost requirements	Manufacturing cost	-	*$/PMT*	0.9270	0.9156	1.0000
		Operate (user costs)	-	*$/PMT*	0.7446	0.6713	1.0000
		Maintenance cost	-	*$/PMT*	0.8956	0.8973	1.0000
	Minimize governmental support	Subsidy	-	*$/PMT*	1.0000	0.9178	0.9943
	Minimize parking requirements	Parking cost	-	*$/PMT*	1.0000	0.1342	0.8762
	Economy sustainability index per city				**0.9134**	**0.7072**	**0.9741**
Users	Maximize transportation performance	Demand	+	*mode types with higher percentage share*	0.6667	0.3333	1.0000
		Global availability	-	*avg. hours of down time or not operable per year expressed as an annual %*	0.8378	1.0000	0.2691
		Reasonable availability	-	*avg. hours of down time or not operable per year expressed as an annual %*	0.9090	1.0000	0.5404
	Maximize user comfort	Passenger space	+	*avg. cu.ft/passenger*	0.9653	1.0000	0.9681
		Goods carrying (cargo) space	+	*avg. cu.ft/passenger*	1.0000	0.9630	0.8196
		Leg room front	+	*avg. in inches*	0.9996	0.9976	1.0000
	Maximize user comfort	Fueling opportunities	+	*avg. fuel stations/veh*	0.1616	0.2140	1.0000
	Users sustainability index per city				**0.7914**	**0.7869**	**0.7996**
	Overall sustainability index per city				**0.8590**	**0.8205**	**0.9545**

The summarized results in Table 6.8 compare the three metropolitan areas based on their SDI and OSI.

Table 6.8. Summary of Metropolitan Area SDI and OSI

Index	Atlanta	Chicago	OPTIMUS
Environment	0.880	0.887	1.000
Technology	0.845	0.842	0.999
Energy	0.864	0.880	1.000
Economy	0.913	0.707	0.974
Users	0.791	0.787	0.800
Overall Sustainability	**0.859**	**0.820**	**0.954**

As expected, OPTIMUS has the highest scores for environment, technology and energy categories by achieving almost 100% of these dimensions of sustainability, but it is less superior in sustainability performance in the other two dimensions. Table 6.8 shows that OPTIMUS achieves 95.4% of overall sustainability while Atlanta and Chicago achieve 85.9% and 82.0%, respectively. Atlanta shows a high economic sustainability performance (91.3%) compared with Chicago (70.7%), which is the factor that contributes most to their OSI difference. The differences for Atlanta and Chicago for the rest of the dimensions are marginal; therefore the OSI between those two cities is skewed by the sustainability dimension Economy. A more careful look of the Economy indicators in Tables 6.5 and 6.7, shows that the indicator that generates the difference is the “parking cost.” High differences in this value between OPTIMUS and Atlanta compared with Chicago, resulted to high differences between normalized values. That suggests that more indicators might be required in each dimension to lessen the impact of individual indicators with extreme values. Another approach could be the utilization of weights. Assignment of lower weights to single indicator with extreme values could lessen their effect.

While the results show that the Atlanta and Chicago are comparable to OPTIMUS in terms of users sustainability, greater discrepancies can be seen for environmental, technology, energy and economy sustainability. Chicago performs better than Atlanta in environment and energy dimension but its economic performance is lower than Atlanta's. While Chicago is more environmental friendly and energy efficient, Chicago economic sustainability performance is affected by more tax credits, higher gasoline and diesel cost and higher cost of parking. Such measures and policies reveal the initial tradeoffs that exist between environmental, energy and economic performance. The higher percentage of vehicle ownership for Atlanta versus Chicago is an additional factor for the environmental and energy sustainability performance. Technology dimension presents similar values for Atlanta and Chicago due to the high number of ICEVs that overshadow other vehicle types when the weighted mean is used. The three Technology indicators that affect the SDI for Atlanta, Chicago and OPTIMUS are the fuel and maintenance frequency, and vehicle storage. These three indicators are estimated by considering the average value per passenger to show the effect on passengers per metropolitan area. For OPTIMUS the results are affected by the vehicle ownership ratio and the lower percentage of total trips relative to Atlanta and Chicago. Technology has the potential to make a bigger difference for other urban transportation modes such as rail and personal rapid transit, where the benefits per passenger for those three indicators will be more obvious.

The sustainability dimension Users is affected greatly by the vehicle availability indicators (i.e., global and reasonable availability), as shown in Table 6.7. The long charging duration for EVs lowers the sustainability performance as shown from the low value (i.e., 0.269) obtained for OPTIMUS for the indicator "global availability" due to the increased EV share. As was mentioned for economy indicators, such effects should be treated, such as removing or decreasing the weight for those indicators, to avoid favoring one alternative over the other based on individual indicators.

The subsidy indicator accounts for tax credits in alternative fuel vehicles and for public transit subsidies. When it is weighted per PMT, the subsidy for alternative fuel vehicles was found not to worsen significantly the economy performance. Therefore, a tax credit might be an effective measure to promote alternative fuel vehicles when they are combined with transportation policies that promote carpooling.

Figure 6.2 illustrates the sustainability performance for each metropolitan area. The pentagon in Figure 6.2, is a tool for visualizing sustainability; it assists decision makers in understanding how the three metropolitan areas perform in each sustainability dimension.

With normal pentagon's full area being the maximum achievable sustainability for a metropolitan area; the pentagons' area that corresponds to the three assessed metropolitan areas, Chicago, Atlanta and OPTIMUS, show the relative level of overall sustainability for those three alternatives. The four way arrows in the center of the pentagon show that the goal of decision makers should be the expansion of each pentagon's sides towards the sides of the normal pentagon, to maximize sustainability performance.

Inclusion of a CS program in OPTIMUS metropolitan area did not change significantly the estimated SDI and OSI for each metropolitan area. The low percentage (i.e., 0.01%) of CS program, estimated on the nearest round based on U.S. averages, produced a marginal change to the sustainability performance of OPTIMUS (visible only to five decimal estimates of SDI and OSI.) The results revealed that the life cycle tool correctly accounted for the very low percentage share of the market for the CS program.

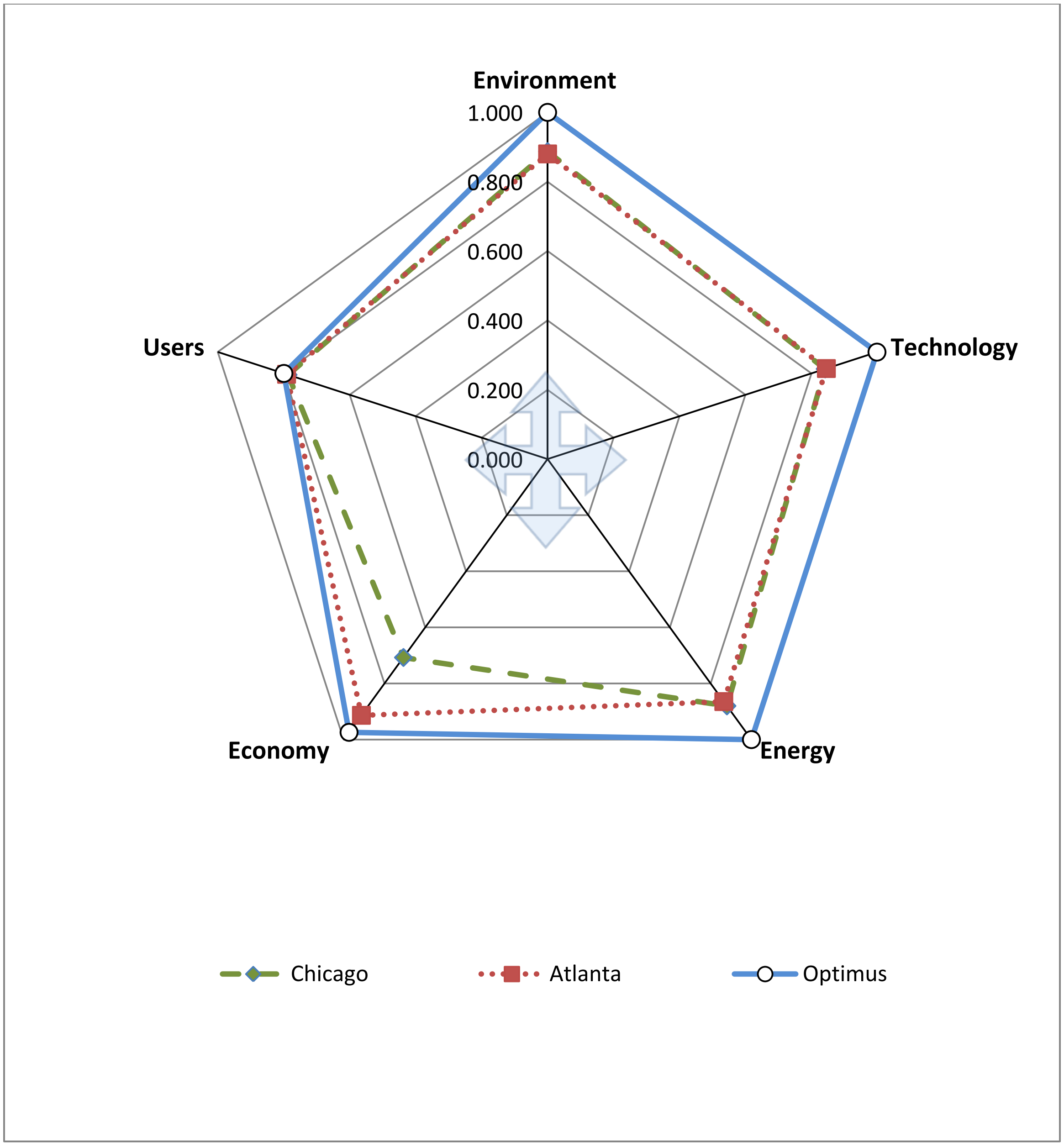

Figure 6.2. Visual Representation of SDI for three Metropolitan Area

Tables 6.6 to 6.7, reveal the fluctuations between sustainability indicators. Those fluctuations reveal which indicators contribute more or less to the estimation of SDI and OSI for different alternatives. As mentioned earlier in this case study, some SDIs for the three metropolitan areas present large discrepancies whereas others change slightly for the same sustainability dimension when compared with each other. Based on SDI values, decision makers should examine the sustainability indicators under each sustainability dimension and determine those indicators that affect more the SDI. In this way, decision makers will be able to determine the sensitivities of one policy over another (e.g., higher gas tax, lower electricity rates etc.), by providing improved services to users (e.g., increase charging points, faster charging stations for public use, etc.) or choosing scenarios that combine one or more of the above measures.

The life cycle sustainability tool can be expanded to provide evaluation of the impact of any transportation infrastructure and management scheme such as fixed guideway for public transit, HOT lanes, price congestion, etc. The SDI and OSI for given alternatives have the potential to support decisions in transportation planning by considering life cycle impacts.

CHAPTER 7

CONCLUSIONS

This chapter provides a summary of this research, the main conclusions, limitation and directions for future research.

7.1. Summary

The primary goal of this dissertation is the development of a life cycle sustainability framework (LCSF), which uses disaggregated performance measures for the assessment of urban transportation modes and assists decision makers in evaluating transportation plans and policies based on sustainability performance. A traditional transportation mode evaluation is based on demand and supply comparisons, cost and benefit evaluations, financial risks analysis, and cost-effectiveness analysis. Recent assessments begin to focus on detailed energy requirements and pollution emissions during the operational stage whereas other applications attempt to internalize the cost of accidents and travel delays. In short, there are multiple view points for assessing modes of transportation due to their important and pervasive impacts to society and economy, both positive and negative. However, a framework that has the potential to assess the long term sustainability of any transportation mode throughout its life cycle is not available. This research effort attempts to close this void in the state of the art starting with a framework that has its foundations in the over-arching principle of sustainability.

Attempts at incorporating sustainability into transportation planning have resulted in research on the development of variables defined as measures, indicators or indices representing elements of sustainability. However, major components of sustainable transportation are omitted in this approach, including infrastructure construction, vehicle manufacture, fueling, maintenance and disposal. The common approach of transportation sustainability considers only personal vehicles or all modes present on a section of a network by using aggregated measures to evaluate sustainability performance (Black et al. 2006, Jeon et al. 2008, Litman 2009, Maoh and Karanoglou 2009, CTS 2002, Zietsman et al. 2003.) The aggregation of transportation performance measures limits one of sustainability's roles in transportation planning, which is to assist agencies in evaluating new transportation modes that are proposed for introduction in a network.

The accelerated development and introduction of vehicles with alternative propulsion systems compel a detailed breakdown of vehicle components and characteristics for the proper understanding of their performance and impacts over their entire life cycle. Disaggregation per vehicle type in a transportation network and life cycle sustainability assessment for each type may lead to more accurate planning and policy making. Sustainability assessment per vehicle type reveals the critical characteristics for considered vehicles and determines the tradeoffs for different indicators.

7.1.1. Sustainability and Life Cycle Assessment in Transportation

Sustainability is a broad concept that can be applied to any system. Our literature review on sustainability definitions and metrics identified that a standard definition that underlies the development of a holistic and comprehensive framework that can be used in the assessment of transportation systems is not available. While there is no standard sustainability definition, framework or indicators for assessing a transportation system, there are common characteristics and objectives such as the mobility of people and goods, accessibility, safety and minimization of emissions that are shared between public and private transportation providers. Sustainability assessment, while utilizing indicators that are grouped into the three major sustainability dimensions (i.e., environment, society, economy) and cross boundaries, impede understanding of sustainability performance and implementation of strategies in transportation.

Life cycle assessment (LCA) has been used extensively in the transportation sector to determine the life cycle environmental impacts of transportation infrastructure and other components. There are only a few studies that describe the incorporation of the LCA methodology in sustainability assessment. In this dissertation the LCA methodology was expanded, enriched and incorporated into the sustainability assessment of transportation urban modes as the most promising methodology for providing comprehensive results.

7.1.2. Life Cycle Sustainability Framework

In developing a LCSF, the generic structure components of a transportation system and the restrictions that may be faced in its development and implementation were considered. The LCSF consists of seven fundamental dimensions that govern transportation systems: (1) Environment; (2) Technology; (3) Energy; (4) Economy, (5) Users and other stakeholders, (6) Legal framework, and (7) Local restrictions. According to the proposed framework, a prism is used as a visual representation to depict the dependence that each sustainability dimension exerts on the next one. The transportation components and their attributes are taken into account for the implementation of the framework to transportation planning; with the components being the vehicle and the infrastructure. The attributes of vehicles and infrastructure are: manufacture, fuel, operation, and maintenance for vehicle, and construction, fuel, operation, and maintenance for the infrastructure. Consideration of these attributes becomes more important when different technologies and fuel types are used in transportation planning.

7.1.3. Sustainability Assessment of Vehicles and Metropolitan Areas

Using the LCSF and the developed indicators, 7 light-duty vehicles, a car-sharing program with 2 different types of vehicles and 2 public transit buses are assessed to compare their sustainability performance. Assessed vehicle types and propulsion options examined in this research include internal combustion engine vehicle, hybrid electric vehicle, fuel cell vehicle, electric vehicle, plug-in hybrid vehicle, internal combustion engine pickup truck, internal combustion engine sports utility vehicle, diesel bus, bus rapid transit and car-sharing program. The sustainability indicators were quantified, normalized and aggregated into a sustainability index for each dimension and overall by using a multi criteria decision making methodology to compare vehicle sustainability performance. The simulation of fuel pathways and vehicle types was made for the year 2010 and the most representative vehicles for each vehicle type were used.

The sustainability assessment for vehicles was followed by a sustainability assessment of metropolitan areas to (1) test and explore the applicability of the results at an aggregated level by using the specific characteristics of each metropolitan area, and (2) reveal the tradeoffs that occur from decision making in transportation planning.

The case study combined the sustainability assessment results for vehicles with transportation data for three metropolitan areas to perform a sustainability assessment of their transportation system. Atlanta, Chicago, and a hypothetical metropolitan area called OPTIMUS (Optimal Transportation Indicators for Modeling Urban Sustainability) are used in this transportation sustainability assessment. OPTIMUS combines optimal and average characteristics from U.S. metropolitan areas. Data are collected from several literature sources. Household travel surveys are used to extract transportation data for Atlanta and Chicago. The weighted sum model methodology was used to aggregate indicator normalized values into a sustainability dimension index (SDI) and an overall sustainability index (OSI). The sustainability assessment results are supported by a visual interface, a regular pentagon, to illustrate sustainability dimension and overall sustainability levels and to allow decision makers and policy analysts to explore variations and tradeoffs in sustainability performance. The SDI is a dimensionless measure that is used to compare the relative sustainability performance between assessed alternatives for each sustainability dimension. Both SDI and OSI are used to reveal dimension specific and overall sustainability tradeoffs occurring for each alternative when different characteristics, policies, scenarios and assumptions are used. The results of the research are presented in the following section.

7.2. Conclusions

The accelerated development and introduction of vehicles with alternative propulsion systems within the next years compel a detailed breakdown of vehicle components and characteristics for the proper understanding of their performance and impacts over their entire life cycle. Disaggregation per vehicle type in a transportation network and life cycle sustainability assessment may lead to more accurate planning and policy making. Incorporation of sustainability into transportation planning process was explored by the development of a LCSF that disaggregates vehicle characteristics by technology and by fuel type.

This dissertation presents a comprehensive sustainability assessment for urban transportation modes published to date by considering life cycle impacts. The outcome of this research is a life cycle sustainability tool that can be expanded, modified and utilized to provide a sustainability assessment at a global or regional level. The life cycle sustainability assessment performed on vehicles produced these findings:

- Operations' based environmental sustainability assessment given diverse vehicle characteristics can be deficient and misleading compared with life cycle results.
- Advanced technologies, such as FCV, EV and PHEV have higher SO_x emissions compared with ICEV and HEV, which occur from the fabrication processes of materials such as aluminum and copper that are used for several components of the traction motor, the electronic controller and the generator.
- GHG emissions for AFVs are increasing dramatically for the fuel production stage compared with gasoline based vehicles due to the production process. This is true especially for the production of electricity for EVs. EVs are not zero emission vehicles as advertised when life cycle results are considered. Upstream emissions (i.e., emissions from recovery, storage, transportation of primary fuel source, and refining and generation of electricity) are a significant environmental component and should be accounted in sustainable transportation planning.
- The vehicle rankings for energy consumption are similar with the vehicle rankings of GHG emissions of each vehicle over their lifetime. This reveals the relationship that exists between energy consumption and GHGs – mainly for CO_2 emissions – as used energy sources are mainly non-renewable and they emit CO_2 emissions.

- Vehicle sustainability rankings change significantly when the life cycle results for emissions and energy are weighted by VMT and PMT. The important and interdependent role of policies on the sustainability performance of a transportation system and how these may shift an environmental unsustainable transportation mode to a sustainable one by changing vehicle occupancy policies is shown by the results.
- Emission intensity and sources differ for each vehicle type. For example, while ICEV produces more CO_2 emissions during its operation, EV produces more CO_2 during the production of its fuel. Policy formulation for treating impacts related to emissions should be based on the number and intensity of emission sources for each region.
- Technology indicators for vehicles such as frequency of fueling/charging and maintenance present large fluctuations and they are proved to be unfavorable for AFVs; especially for those that are powered entirely or partially by electricity due to long charging duration.
- User indicators related to the unavailability of a vehicle during a 24 hour period present high differences between assessed alternatives. Development and improvement on the range of electric battery packs will be the key for users to accept EVs. This indicator will influence users to perceive EVs negatively as the miles driven per day increase and positively as the availability of charging stations increases for a region.
- The most energy demanding vehicles were found to be the GSUV and the GTP with energy consumption of 11.61 and 7.70 Mj/PMT, respectively.

- The HEV and the FCV were found to require the lowest energy amount over their lifetimes (i.e., weighted per VMT.) Their energy requirements are 44% lower than the energy requirements of an ICEV, and 64% lower than that of a GPT. The CS program with HEV technology and the BRT system have the lowest energy consumption per PMT.
- The overall sustainability indices indicate that the most sustainable vehicles are the CS and the BRT system. The CS program with a HEV attained the highest percentage of sustainability with 95%; the CS program with an ICEV and the BRT system were ranked second with 92% and third with 87% of sustainability attainment, respectively.
- The most promising technologies for Environment, Technology, Energy and Economy, between private passenger cars, were found to be the HEV, the FCV and the EV.
- The FCV comes first, between passenger cars, in the sustainability dimension of Environment with a significant difference from all others. The sustainability dimension index is 25% higher compared with the second best passenger car (i.e., the HEV) in the sustainability dimension Environment.
- Private passenger vehicles were ranked in order of highest to lowest score, with FCV, HEV, PHEV, EV, GSUV, ICEV and GPT achieving 69.7%, 67.2%, 66.8%, 64.5%, 56.7%, 55.2%, and 32.3%, of the possible maximum overall sustainability, respectively.

The case study that presented the sustainability assessment of metropolitan areas by using life cycle sustainability results for individual vehicle technologies and fuels is the first to estimate transportation sustainability performance for an entire region. The sustainability indicators used herein represent the five sustainability dimensions (i.e., Environment, Technology, Energy, Economy and Users) of the LCSF and they are aggregated to compare Atlanta, Chicago and OPTIMUS metropolitan areas. The case study showed that the LCSF can be applied to different transportation networks by considering their transportation and demographic characteristics and has the potential to provide detailed sustainability inventories given representative regional data.

The assessment of metropolitan areas revealed the best alternative based on their relative sustainability performance. The multidisciplinary character of sustainability is decomposed by using five sustainability dimensions that set more distinguishable boundaries between impacts and actions that have to be taken to improve sustainability, compared with the traditional three bottom line approach. Towards this goal, the SDI combined with a tool that visualizes SDI magnitudes and provides sufficient information to decision makers and policy analysts on the dominant alternative. OSI and SDI values set the starting point for exploring the contribution of each vehicle type and its impacts on the sustainability performance of a metropolitan area. Identification of those impacts may set priorities and develop weights that can be used in decision making for an efficient and sustainable transportation planning.

The substantial impacts of transportation on environment, society and economy strongly urge the incorporation of sustainability into transportation planning. This dissertation updates the state of the art in three main areas: (1) It takes a well-to-wheel approach of modes instead of focusing only on the operation of modes, (2) it disaggregates modes instead of focusing on personal vehicles; and, (3) it explicitly assesses most current fuels and propulsion technologies instead of focusing on fossil fuel powered modes. The method can be used for any mode of transportation including light and heavy rail, ferries and airplanes. The requirements for applying this method is having the quantities of materials used to build the "vehicle", its operating characteristics, and estimates of its usage such as ridership, load factors, etc.

Given the extensive level at which the method was applied and demonstrated herein, it can be surmised that the proposed method is both detailed and manageable. It has the potential to provide comparisons by **mode** (e.g., private vehicle with technology X vs. bus), by **system** (e.g., BRT vs. Light Rail), by **corridor** (e.g., HOT lanes vs. Mass Transit for a given corridor), and by **area** (e.g., comparisons of sections in the same city, or comparisons among cities or metro areas.) The results are technology and policy sensitive, thus useful for both short and long term planning.

7.3. Limitations and Future Work

The LCSF and the methodology presented in this dissertation are suitable for the analysis of various systems of urban infrastructure, with suitable modifications. These specifications refer to the indicators that must be determined to assess the subject system.

The high number of data sources and assumptions in sustainability studies that utilize criteria and indicators to assess alternatives impose limitations and uncertainties as described below. The future work described below is related to the limitations of this study and to additional possibilities of life cycle sustainability assessment in transportation.

- The LCSA inventories for vehicles are based on built-in assumptions and parameters in GREET, MOBILE and EIO-LCA models. GREET and MOBILE outputs are more accurate compared with results generated by EIO-LCA. EIO-LCA uses aggregated economic sectors that are too large for a detailed analysis on specific products and the estimated impacts refer to the "average" product impacts.
- The estimated sustainability results rely on the characteristics of the "best-selling vehicle", which represents a whole class of vehicles. In order to conduct a more detailed LCA, it was attempted to determine the exact material compositions for each vehicle. A questionnaire was developed and distributed to the design centers of automobile companies to inquire their input related to vehicle components for specific models. The questionnaire could not be completed due to companies' policy.
- The LCA uses the same analysis boundaries for all vehicles and excludes from the assessment their supporting components of transportation sector. The assessment captures all the life cycle stages for a well-to-wheel analysis and considers additional components for the operational stage of vehicles. The author accepts that the components included in this LCSA have the largest impact contribution on vehicles sustainability and can be characterized as "primary" to show the direct impact to users and stakeholders. However, supporting components such as energy plants, fueling stations, management of public transit are not included. Inclusion of additional components would relate first to the infrastructure and service components that are different and necessary for the operation of all

vehicles and then to secondary components that are related to manufacturing, fuelling and maintenance of vehicles.

- The selected LCA tools are robust but do not account for significant environmental impacts, such as water requirements and in some case supporting industries. Although water is one of the potential effects used to measure environmental performance under ISO 14040, the majority of LCA tools do not account for it. Water footprint for transportation fuels is estimated based on literature sources and this can be expanded to other life cycle stages after extensive research.
- Data that affects all sustainability dimensions such as fuel prices, vehicle costs, weights, material components, effectiveness of charging and fueling stations and so on is updated continuously and may change substantially over time. In the analysis of this study the most recent data sources are used. Although globalization may have led to a flattening of local values, it is quite probable that industrial quantities, processes and costs vary by country or region.
- Life cycle inventory weighting by VMT and PMT was necessary for the comparison of vehicles given different properties. Two functional units were selected to eliminate weighting biases between on-road vehicles but this approach may not provide comparable results for vehicles that serve different needs (i.e., cars versus boats versus airplanes for an intercity travel comparison.) The method is flexible and customizable by indicators selection and by weights to deliver a "pair" sustainability assessment.

- The mileage and the fuel efficiency are assumed to be stable over a vehicle's lifetime and any deterioration to their performance and increasing generation of emissions over time is not considered. The average mileage and fuel efficiency over vehicle lifetime can be used to provide results that account for those changes, given that such data are available. Data for AFV performance and deterioration for their fuel efficiency is not yet available. Critically, the long term performance of high capacity batteries in EVs is unknown.
- EV and PHEV material compositions are not covered in the present edition of GREET. Therefore the material compositions for the EV and PHEV are based on assumptions from the ANL report and on our assumption of 80% HEV and 20% ICEV mix. GREET has announced the inclusion of other vehicle types in future versions and it provides updates on new pathways for alternative fuels, new options to account for energy uses and emissions associated with the construction of petroleum and natural gas wells, and coal mines and updated petroleum recovery and refining estimates.

These limitations are not fatal and overall results may be improved by sensitivity analysis of critical parameters like fuel prices and ridership estimates. Future research should include a sensitivity analysis, which may reveal how changes in the assumed parameters of vehicles can change the final outcome for assessing transportation modes and identify the switch over point of assumed parameters where different vehicles provide marginal improvements. Values that are subject to a high degree of uncertainty can be treated by using probability distributions. GREET has a built in function that takes into account the probability distributions of key input parameters such as energy efficiencies and emission factors associated with the feedstock recovery and fuel production processes, and produces results in the form of statistical distributions. Additionally, the multi criteria decision making methodology can use a non-deterministic approach (e.g., Bayesian decision theory and the Bayesian networks) to make decisions in the face of uncertainty, or when the available data are imprecise, incomplete, or inconsistent, and in which outcomes can be uncertain.

The methodology used for the LCSA of vehicles and metropolitan areas ranked the alternatives based on the level of relative sustainability rather than on absolute sustainability levels. In the assessment of metropolitan areas, the alternatives' were compared with OPTIMUS – a hypothetical metropolitan area that achieves the maximum possible sustainability – and it can be used as a scale of sustainability performance.

For the sustainability dimension Technology the introduction of more advanced indicators describing engine performance or special features that can affect vehicle implementation and usage should be researched and introduced. The sustainability dimension Users can embrace indicators that are related to human behavior and specific vehicle characteristics that affect users' mode choice. These characteristics can supplement the generalized ones presented in this research or they can be corridor or region specific to represent passenger needs (e.g., vehicles that connect airport/ports to city centers should accommodate passengers' luggage needs, vehicles serving touristic places should accommodate passengers equipment for entertainment, vehicles serving regions with occasional extreme weather conditions should provide protection to passengers, etc.)

Safety which is a major component of transportation can be a separate object of sustainability research due to its interactions with socioeconomic and demographic characteristics of a region. Data for the assessment of alternative fuel vehicles' safety performance that is related to new vehicle features, such as quieter engine at lower speeds, different fuels and fuel storage systems, utilization of lighter materials and so on, may be based initially on laboratory experiments rather on road experience. Safety assessment will be effective when statistics on the number of people injured and on severities of their injuries become available per vehicle type.

Purchase costs for alternative fuel vehicles were based on prices provided by automobile companies and do not take into account any economies of scale. Market demand for those vehicle types may be insufficient at present to establish a stable price as the effect of automobile companies' expanded scale of production in the long run. Scale economies should be exploited and taken into consideration when advanced vehicle technologies are included in the assessment.

Application of transportation policies in combination with alternative fuel vehicles and public transit modes to study the sensitivity of various life cycle sustainability indicators can be performed. This dimension of the research would be able to assess the efficacy of policies such as incentives to specific vehicle technologies for specific cities. The analysis can be performed for peak and off-peak times instead of average conditions and also can include vehicle speed distributions per VMT.

The LCSF decomposed the mode into the components of vehicle and infrastructure. This dissertation was focused on the component vehicle and specifically on urban road vehicles to perform a LCSA. Infrastructure and land use planning are major components of transportation and are interdependent with the operation of vehicles. A LCSA of additional vehicles and types of supporting infrastructure can provide a complete picture of the sustainability performance of any transportation mode over its life cycle. The assessment can be supplemented by including “green” materials vis-à-vis traditional materials for infrastructure construction.

Due to the multidisciplinary character of sustainability, the indicators proposed for the LCSA of vehicles as well as their interactions can be the objective of research for the better understanding of their role in transportation sustainability. The sustainability LCSF with its proposed indicators should provide the basis for sustainability assessment in transportation planning. The framework can be enhanced with additional indicators to monitor sustainability progress on a year-by-year basis.

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APPENDIX A. DEFINITIONS OF VEHICLE PARTS

Body-in-white	Primary vehicle structure, usually a single-body assembly to which other major components are attached
Body panels	Closure panels and hang-on panels, such as the hood, roof, decklid, doors, quarter panels, and fenders
Front/rear bumpers	Impact bars, energy absorbers, and mounting hardware
Body hardware	Miscellaneous body components
Glass	Front windshield, rear windshield, and door windows
Paint	E-coat, priming, base coats, and clear coats
Exterior trim	Molding, ornaments, bumper cover, air deflectors, ground effects, side trim, mirror assemblies, and nameplates
Body sealers/deadeners	All rubber trim
Exterior lighting	Head lamps, fog lamps, turn signals, side markers, and tail light assemblies
Instrument panel module	Panel structure, knee bolsters and brackets, instrument cluster, exterior surface, console storage, glove box panels, glove box assembly and exterior, and top cover
Trim and insulation	Emergency brake cover, switch panels, ash trays, arm rests, cup holders, headliner assemblies, overhead console assemblies, assist handles, coat hooks, small item overhead storage, pillar trim, sun visors, carpet, padding, insulation, and accessory mats
Door module	Door insulation, trim assemblies, speaker grills, switch panels and handles (door panels are considered as part of the body panels category)
Seating and restraint system	Seat tracks, seat frames, foam, trim, restraints, anchors, head restraints, arm rests, seat belts, tensioners, clips, air bags, and sensor assemblies
Heating, ventilation, air conditioning (HVAC) module	Air flow system, heating system, and air conditioning system (which includes a condenser, fan, heater, ducting, and controls)
Interior electronics	Wiring and controls for interior lighting, instrumentation, and power accessories

Figure A1.Vehicle Body System

Engine unit	Engine block, cylinder heads, fuel injection, engine air system, ignition system, alternator, and containers and pumps for the lubrication system
Fuel cell stack	Membrane electrode assembly, bipolar plates, gaskets, current collector, insulator, outer wrap, and tie bolts
Engine fuel storage system	Fuel tank, tank mounting straps, tank shield, insulation, filling piping, and supply piping
Powertrain thermal system	Water pump, radiator, and fan
Exhaust system	Catalytic converter, muffler, heat shields, and exhaust piping
Powertrain electrical system	Control wiring, sensors, switches, and processors
Emission control electronics	Sensors, processors, and engine emission feedback equipment

Figure A2.Vehicle Powertrain System

Transmission unit	Gearbox, torque converter, and controls
ICEV	Uses an automatic transmission and therefore a torque converter
HEV	Uses a type of continuously variable transmission with a planetary gear set and therefore does not have a torque converter
FCV	Weighs approximately one-third less than the HEV transmission and consists of a single-ratio gearbox and no torque converter (Bohn 2005)

Figure A3. Vehicle Transmission System

ICEV	Pb-Ac battery to handle the startup and accessory load
HEV/FCV	Pb-Ac battery to handle the startup and accessory load and either an Ni-MH or Li-ion battery for use in the electric-drive system

Figure A4.Vehicle Battery System

ICEV/HEV	Engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives
FCV	Power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives

Figure A5.Vehicle Fluid System

Cradle	Frame assembly, front rails, and underbody extensions, cab and body brackets (the cradle bolts to the BIW and supports the mounting of the engine/fuel cell)
Driveshaft/axle	A propeller shaft, halfshaft, front axle and rear axle (the propeller shaft connects the gearbox to a differential, while the halfshaft connects the wheels to a differential)
Differential	A gear set that transmits energy from the driveshaft to the axles and allows for each of the driving wheels to rotate at different speeds, while supplying them with an equal amount of torque
Corner suspension	Upper and lower control arms, ball joints, springs, shock absorbers, steering knuckle, and stabilizer shaft
Braking system	Hub, disc, bearings, splash shield, and calipers
Wheels	Four main wheels and one spare
Tires	Four main tires and one spare
Steering system	Steering wheel, column, joints, linkages, bushes, housings, and hydraulic-assist equipment
Chassis electrical system	Signals; switches; horn wiring; and the anti-lock braking system (ABS) wiring, sensors, and processors

Figure A6.Vehicle Chassis System

Generator	Power converter that takes mechanical energy from the engine and produces electrical energy to recharge the batteries and power the electric motor for HEVs
Motor	Electric motor used to drive the wheels
Electronic controller (controller/converter)	Power controller/phase inverter system that converts power between the batteries and motor/generators for electric-drive vehicles
Fuel cell auxiliaries	Compressed hydrogen tank system, water supply system, air supply system, cooling system, and piping system

Figure A7. Electric-Drive System

APPENDIX B. ASSUMPTIONS FOR VEHICLE MATERIALS

Table B1.Material Component Percentages for Lead-Acid, Ni-MH, Li-Ion Batteries

	Gasoline Vehicles	HEV	AFVs
Lead-Acid			
Plastic: Polypropylene	6.1%	6.1%	6.1%
Lead	69.0%	69.0%	69.0%
Sulfuric Acid	7.9%	7.9%	7.9%
Fiberglass	2.1%	2.1%	2.1%
Water	14.1%	14.1%	14.1%
Others	0.8%	0.8%	0.8%
Ni-MH			
Iron		12.0%	12.0%
Steel		23.7%	23.7%
Aluminum		0.5%	0.5%
Copper		3.9%	3.9%
Magnesium		1.0%	1.0%
Cobalt		1.8%	1.8%
Nickel		28.2%	28.2%
Rare Earth Metals		6.3%	6.3%
Average Plastic		22.5%	22.5%
Rubber		0.1%	0.1%
Li-Ion			
Lithium Oxide (LiO2)		5.3%	5.3%
Nickel		2.6%	2.6%
Cobalt		2.7%	2.7%
Manganese		2.5%	2.5%
Graphite/Carbon		10.6%	10.6%
Binder		2.1%	2.1%
Copper		24.5%	24.5%
Wrought Aluminum		18.6%	18.6%
Cast Aluminum		10.6%	10.6%
Electrolyte		8.7%	8.7%
Plastic: Polypropylene		8.1%	8.1%
Plastic: Polyethelene		2.9%	2.9%
Steel		0.2%	0.2%
Thermal Insulation		0.5%	0.5%
Electronic Parts		0.1%	0.1%

Table B2. Tons of Intermediate Material Needed per Ton of Final Steel Product

	Ore Recovery	Ore Pelletizing&Sintering	Coke Production	Blast Furnace	Basic O2 Processing	Electric Arc Furnace	Sheet Production&Rolling	Stamping
Virgin Steel	5.200	1.860	0.531	1.180	1.420	0.220	1.340	1.000
Recycled Steel					0.090	1.530	1.340	1.000
Stainless Steel						1.610	1.340	1.000

Table B3. Tons of Intermediate Material Needed per Ton of Final Wrought Aluminum Product

	Bauxite Mining	Bauxite Refining	Alumina Reduction	Scrap Preparation	Reverb Melt and Ingot Cast	Al Melting and Casting	Sheet Production&Rolling	Stamping
Virgin Wrought Aluminum	4.800	1.900	1.000			1.000	1.380	1.000
Recycled Wrought Aluminum				1.060	1.000	1.000	1.380	1.000

Table B4. Tons of Intermediate Material Needed per Ton of Final Cast Aluminum Product

	Bauxite Mining	Bauxite Refining	Alumina Reduction	Al Melting and Casting	Al Casting	Al Recycling
Cast Aluminum	4.800	1.900	1.000	1.000		
Recycled Cast Aluminum					1.000	1.000

Table B5. Composition of Fiber Glass,% by wt

Glass	Glass Fiber
0.0%	100.0%

Table B6. Shares of Individual Plastic in a Vehicle for Average Plastic Calculation, % by wt

Polypropylene	Polyester	HDPE*
50.0%	30.0%	20.0%

*Higy-density polyethylene.

Table B7. Shares of Individual Plastic in a Vehicle for Average Plastic Calculation, % by wt

	Polyester	Glass Fiber	Inert Filler
Glass Fiber-Reinforced Plastic	50.0%	50.0%	0.0%
	Polyester	Carbon Fiber	
Carbon Fiber-Reinforced Plastic	70.0%	30.0%	

Table B8. Tons of Intermediate Material Needed per Ton of Final Fiber-Reinforced Plastic Product

Glass Fiber-Reinforced Plastic	1.140
Carbon Fiber-Reinforced Plastic	1.140

Table B9. Electric Generation Mixes for Alumina Reduction: Hall-Heroult Process
(Aluminum Smelting)

	Wrought Aluminum	Cast Aluminum
	US Mix	US Mix
Residual oil	1.1%	1.1%
Natural gas	18.3%	18.3%
Coal	50.4%	50.4%
Nuclear power	20.0%	20.0%
Biomass	0.7%	0.7%
Others	9.5%	9.5%

APPENDIX C. MATERIAL QUANTITIES QUESTIONNAIRE FOR VEHICLES

TOYOTA CAMRY- 2.5L, 4CYL

Trim Level (if applicable): Base, 2WD, auto, with a/c

Questions? Please contact Lambros at lampros@hawaii.edu

Return questionnaire by email to the address above or fax to 808-956-5014, or mail to Civil Engineering (c/o Lambros Mitropoulos,) 2540 Dole St, Holmes Hall 383, Honolulu, HI 96822

Required Vehicle Specifications

YEAR

Yellow cells require your input

If upon opening you receive a security warning message please click on "Options..." above the formula bar, select "Enable this content" and click on OK.

% by weight is the portion of each vehicle component as a percentage of the total vehicle weight in cell D8

1. Vehicle Weight, wet in pounds Weight = lbs

2. Weight of Vehicle Battery and Fluids

Battery type	Pounds

Fluids	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Fluid	Adhesives
Weight (pounds)							

3. Key Input Parameters for Vehicle Components: Body, Powertrain System, Transmission System, Chassis

Vehicle Components Composition	% by weight
Powertrain System	
Transmission System	
Chassis (w/o battery)	
Body: including body, interior, exterior, and glass	100.0%

Share of Materials Used in Vehicle, % by weight	Virgin Material	Recycled Material
Steel		100.0%
Wrought Aluminum		100.0%
Cast Aluminum		100.0%
Lead		100.0%
Nickel		100.0%

4. Material Composition for Vehicle Components

Body	% by weight
Steel	
Wrought Aluminum	
Copper/Brass	
Magnesium	
Glass	
Carbon Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%

Powertrain System	% by weight
Steel	
Stainless Steel	
Cast iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Average Plastic	
Rubber	
Carbon Fiber-Reinforced Plastic	
PFSA	
Carbon Paper	
PTFE	
Carbon & PFSA Suspension	
Platinum	
Others	100.0%

Transmission System/Gearbox	% by weight
Steel	
Copper	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Average Plastic	
Rubber	
Others	100.0%

Chassis (w/o battery)	% by weight
Steel	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Glass Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%

COMMENTS:

TOYOTA PRIUS III 1.8L 4-CYL.

Trim Level (if applicable): Base, 2WD, auto, with a/c

Questions? Please contact Lambros at lampros@hawaii.edu

Return questionnaire by email to the address above or fax to 808-956-5014, or mail to Civil Engineering (c/o Lampros Mitropoulos,) 2540 Dole St, Holmes Hall 383, Honolulu, HI 96822

Required Vehicle Specifications YEAR

1. Vehicle Weight, wet in pounds Weight = lbs

Yellow cells require your input

% by weight is the portion of each vehicle component as a percentage of the total vehicle weight in cell D8

2. Weight of Vehicle Battery and Fluids

Battery type	Pounds
Lead-Acid	
Ni-MH	

	Battery Size in Peak Batt. (kW)	Battery Specific Power (W/kg)
Ni-MH		

Fluids	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Wind-shield Fluid	Adhesives
Weight (pounds)							

3. Vehicle Components: Body, Powertrain System, Transmission System, Chassis, Traction Motor, Generator, Electronic Controller

Vehicle Components Composition	% by weight
Powertrain System	
Transmission System	
Chassis (w/o battery)	
Traction Motor	
Generator	
Electronic Controller	
Body: including body, interior, exterior, and glass	100.0%

Share of Materials Used in Vehicle, % by weight	Virgin Material	Recycled Material
Steel		100.0%
Wrought Aluminum		100.0%
Cast Aluminum		100.0%
Lead		100.0%
Nickel		100.0%

4. Material Composition for Vehicle Components

Body	% by weight
Steel	
Wrought Aluminum	
Copper/Brass	
Magnesium	
Glass	
Carbon Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Powertrain System	
Steel	
Stainless Steel	
Cast iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Average Plastic	
Rubber	
Carbon Fiber-Reinforced Plastic	
PFSA	
Carbon Paper	
PTFE	
Carbon & PFSA Suspension	
Platinum	
Others	100.0%
Transmission System/Gearbox	
Steel	
Copper	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Average Plastic	
Rubber	
Others	100.0%

Chassis (w/o battery)	% by weight
Steel	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Glass Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Traction Motor	
Steel	
Stainless Steel	
Cast Aluminum	
Copper/Brass	
Others	100.0%
Generator	
Steel	
Cast Aluminum	
Copper/Brass	
Others	100.0%
Electronic Controller	
Steel	
Cast Aluminum	
Copper/Brass	
Rubber	
Average Plastic	
Others	100.0%

COMMENTS:

NISSAN LEAF

Trim Level (if applicable): Base, 2WD, auto, with a/c

Questions? Please contact Lambros at lampros@hawaii.edu

Return questionnaire by email to the address above or fax to 808-956-5014, or mail to Civil Engineering (c/o Lampros Mitropoulos,) 2540 Dole St, Holmes Hall 383, Honolulu, HI 96822

Required Vehicle Specifications YEAR

1. Vehicle Weight, wet in pounds Weight = lbs

Yellow cells require your input

% by weight is the portion of each vehicle component as a percentage of the total vehicle weight in cell D8

2. Weight of Vehicle Battery and Fluids

Battery type	Pounds
Lead-Acid	
Li-Ion	

	Battery Size in Peak Batt. (kW)	Battery Specific Power (W/kg)
Li-Ion		

Fluids	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Fluid	Adhesives
Weight (pounds)							

3. Vehicle Components: Body, Powertrain System, Transmission System, Chassis, Traction Motor, Electronic Controller

Vehicle Components Composition	% by weight
Powertrain System	
Transmission System	
Chassis (w/o battery)	
Traction Motor	
Generator	
Electronic Controller	
Body: including body, interior, exterior, and glass	100.0%

Share of Materials Used in Vehicle, % by weight	Virgin Material	Recycled Material
Steel		100.0%
Wrought Aluminum		100.0%
Cast Aluminum		100.0%
Lead		100.0%
Nickel		100.0%

4. Material Composition for Vehicle Components

Body	% by weight
Steel	
Wrought Aluminum	
Copper/Brass	
Magnesium	
Glass	
Carbon Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Powertrain System	
Steel	
Stainless Steel	
Cast iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Average Plastic	
Rubber	
Carbon Fiber-Reinforced Plastic	
PFSA	
Carbon Paper	
PTFE	
Carbon & PFSA Suspension	
Platinum	
Others	100.0%
Transmission System/Gearbox	
Steel	
Copper	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Average Plastic	
Rubber	
Others	100.0%

Chassis (w/o battery)	% by weight
Steel	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Glass Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Traction Motor	
Steel	
Stainless Steel	
Cast Aluminum	
Copper/Brass	
Others	100.0%
Electronic Controller	
Steel	
Cast Aluminum	
Copper/Brass	
Rubber	
Average Plastic	
Others	100.0%

COMMENTS:

HONDA FCX CLARITY

Trim Level (if applicable): Base, 2WD, auto, with a/c

Questions? Please contact Lambros at lampros@hawaii.edu
Return questionnaire by email to the address above or fax
to 808-956-5014, or mail to Civil Engineering (c/o Lampros
Mitropoulos,) 2540 Dole St, Holmes Hall 383, Honolulu, HI 96822

Required Vehicle Specifications YEAR

Yellow cells require your input

% by weight is the portion of each vehicle component as a percentage of the total vehicle weight in cell D8

1. Vehicle Weight, wet in pounds Weight = lbs

2. Weight of Vehicle Battery and Fluids

Battery type	Pounds
Lead-Acid	
Li-Ion	

	Battery Size in Peak Batt. (kW)	Battery Specific Power (W/kg)
Li-Ion		

Fluids	Engine Oil	Power Steering Fluid	Brake Fluid	Transmis-sion Fluid	Powertrain Coolant	Wind-shield Fluid	Adhesives
Weight (pounds)							

3. Key Input Parameters for Vehicle Components: Body, Powertrain System, Transmission System, Chassis, Traction Motor, Generator, Electronic Controller, and Fuel Cell Auxiliary System

Vehicle Components Composition	% by weight
Powertrain System	
Transmission System	
Chassis (w/o battery)	
Traction Motor	
Generator	
Electronic Controller	
Fuel Cell Auxiliary System	
Body: including body, interior, exterior, and glass	100.0%

Share of Materials Used in Vehicle, % by weight	Virgin Material	Recycled Material
Steel		100.0%
Wrought Aluminum		100.0%
Cast Aluminum		100.0%
Lead		100.0%
Nickel		100.0%

Fuel Cell Stack Size (kW)

4. Material Composition for Vehicle Components

Body	% by weight
Steel	
Wrought Aluminum	
Copper/Brass	
Magnesium	
Glass	
Carbon Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Powertrain System	
Steel	
Stainless Steel	
Cast iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Average Plastic	
Rubber	
Carbon Fiber-Reinforced Plastic	
PFSA	
Carbon Paper	
PTFE	
Carbon & PFSA Suspension	
Platinum	
Others	100.0%
Transmission System/Gearbox	
Steel	
Copper	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Average Plastic	
Rubber	
Others	100.0%

Chassis (w/o battery)	% by weight
Steel	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Glass Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Traction Motor	
Steel	
Stainless Steel	
Cast Aluminum	
Copper/Brass	
Others	100.0%
Electronic Controller	
Steel	
Cast Aluminum	
Copper/Brass	
Rubber	
Average Plastic	
Others	0.0%
Fuel Cell Auxiliary System	
Steel	
Carbon Fiber-Reinforced Plastic	
Wrought Aluminum	
Copper	
Average Plastics	
Rubber	
Nickel	
Others	100.0%

COMMENTS:

CHEVY VOLT

Trim Level (if applicable): Base, 2WD, auto, with a/c

Questions? Please contact Lambros at lampros@hawaii.edu

Return questionnaire by email to the address above or fax

to 808-956-5014, or mail to Civil Engineering (c/o Lampros

Mitropoulos,) 2540 Dole St, Holmes Hall 383, Honolulu, HI 96822

Required Vehicle Specifications YEAR

Yellow cells require your input

% by weight is the portion of each vehicle component as a percentage of the total vehicle weight in cell D8

1. Vehicle Weight, wet in pounds Weight = lbs

2. Weight of Vehicle Battery and Fluids

Battery type	Pounds
Lead-Acid	
Li-Ion	

	Battery Size in Peak Batt. (kW)	Battery Specific Power (W/kg)
Li-Ion		

Fluids	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Wind-shield Fluid	Adhesives
Weight (pounds)							

3. Vehicle Components: Body, Powertrain System, Transmission System, Chassis, Traction Motor, Generator, Electronic Controller

Vehicle Components Composition	% by weight
Powertrain System	
Transmission System	
Chassis (w/o battery)	
Traction Motor	
Generator	
Electronic Controller	
Body: including body, interior, exterior, and glass	100.0%

Share of Materials Used in Vehicle, % by weight	Virgin Material	Recycled Material
Steel		100.0%
Wrought Aluminum		100.0%
Cast Aluminum		100.0%
Lead		100.0%
Nickel		100.0%

4. Material Composition for Vehicle Components

Body	% by weight
Steel	
Wrought Aluminum	
Copper/Brass	
Magnesium	
Glass	
Carbon Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Powertrain System	
Steel	
Stainless Steel	
Cast iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Average Plastic	
Rubber	
Carbon Fiber-Reinforced Plastic	
PFSA	
Carbon Paper	
PTFE	
Carbon & PFSA Suspension	
Platinum	
Others	100.0%
Transmission System/Gearbox	
Steel	
Copper	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Average Plastic	
Rubber	
Others	100.0%

Chassis (w/o battery)	% by weight
Steel	
Cast Iron	
Wrought Aluminum	
Cast Aluminum	
Copper/Brass	
Glass Fiber-Reinforced Plastic	
Average Plastic	
Rubber	
Others	100.0%
Traction Motor	
Steel	
Stainless Steel	
Cast Aluminum	
Copper/Brass	
Others	100.0%
Generator	
Steel	
Cast Aluminum	
Copper/Brass	
Others	100.0%
Electronic Controller	
Steel	
Cast Aluminum	
Copper/Brass	
Rubber	
Average Plastic	
Others	100.0%

COMMENTS:

APPENDIX D. ENERGY REQUIREMENTS OF VARIOUS MATERIALS

Table D1.Energy Use of Steel Production: mmBtu per ton of material product

0.054	Taconite Mining
1.391	Ore Pelletizing & Sintering
5.580	Coke* Production
15.886	Blast Furnace
1.627	Basic O2 Processing
4.240	Electric Arc Furnace (for virgin steel and recycled steel)
4.819	Electric Arc Furnace (for stainless steel)
6.108	Sheet Production & Rolling
5.453	Stamping

*Energy allocation method is applied for coking process. The energy use is assumed equally among same energy unit of coke, COG and byproduct.

Table D2. Energy Use of Cast Iron Production: mmBtu per ton of material product

1.339	Iron Recycling
20.664	Iron Casting

Table D3. Energy Use of Wrought Aluminum Production: mmBtu per ton of material product

0.563	Bauxite Mining
9.527	Bauxite Refining: Bayer Process
65.843	Alumina Reduction: Hall-Heroult Process
4.146	Al Melting and Casting
8.344	Sheet Production & Rolling
5.453	Stamping
0.623	Scrap Preparation (Recycled Al)
9.500	Reverb Melt and Ingot Cast (Recycled Al)

Table D4. Energy Use of Lead Production: mmBtu per ton of lead

2.590	Lead Ore Mining
15.006	Virgin Lead Production
4.140	Recycled Lead Production

Table D5. Energy Use of Nickel Production: mmBtu per ton of nickel or nickel hydroxide

0.000	Nickel Ore Mini
63.781	Nickel Producti
15.945	Recycled Nickel Production
4.918	Nickel Hydroxide Production
2.459	Recycled Nickel Hydroxide Production

Table D6. Energy Use of Cobalt Production: mmBtu per ton of cobalt oxide

0.000	Ore Mining
63.781	Cobalt Oxide Production
15.945	Recycled Cobalt Oxide Production

Table D7. Energy Use of Copper Production: mmBtu per ton of copper

0.000	Ore Mining
65.962	Copper Production

Table D8. Energy Use of Zinc Production: mmBtu per ton of zinc

3.720	Ore Mining
86.400	Zinc Production

Table D9. Energy Use of Magnesium Production: mmBtu per ton of magnesium

0.000	Ore Mining
167.000	Magnesium Production

Table D10. Energy Use of Glass Production: mmBtu per ton of material product

14.824	Glass Production
14.021	Glass Fiber Production

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Table D11. Energy Use of Plastic Production: mmBtu per ton of material product

28.400	Polypropylene Production
61.161	Polyester Production
33.000	HDPE Production
0.641	Inert Filler Production
160.200	Carbon Fiber Production
7.886	Glass Fiber-Reinforced Plastic Fabrication
7.886	Carbon Fiber-Reinforced Plastic Fabrication

Table D12. Energy Use of Rubber Production: mmBtu per ton of rubber

33.855	Styrene-butadiene Rubber Production

Table D13. Energy Use of Platinum Production: mmBtu per ton of platinum

2.262	Ore Mining*
72.100	Platinum Processing

*Data from North American Mining Company

Table D14. Energy Use of Rare Earth Production: mmBtu per ton of rare earth

4.333	Ore Mining*
108.314	Virgin Rare Earth Production*
0.000	Recycled Rare Earth Production

* Japanese Data.

Table D15. Energy Use of Manganese Production: mmBtu per ton of manganese

3.720	Ore Mining
86.400	Virgin Manganese Production

Table D16. Energy Use of Fuel-Cell Materials Production: mmBtu per ton of material product

12.296	Nafion 117 Sheet Production
12.038	Nafion Dry Polymer Production
81.685	PTFE Production

Table D17. Energy Use of Fluids Production: mmBtu per ton of material product

29.654	Ethylene Glycol Production

APPENDIX E. SELECTED U.S. DATA BY STATE AND CITY

Table E1. Gas, Electric and Hydrogen Stations per Million Capita per State

State or territory	Census population 2010	Gas Stations	Gas stations per 10^6 cap.	Electric Stat.	H_2 Stat.	Electric stations per 10^6 cap.	H_2 stations per 10^6 cap.
Alabama	4,779,736	720	151	4	0	0.84	0.00
Alaska	710,231	57	80	0	0	0.00	0.00
Arizona	6,392,017	393	61	39	1	8.16	0.21
Arkansas	2,915,918	308	106	11	0	2.30	0.00
California	37,253,956	4242	114	992	23	207.54	4.81
Colorado	5,029,196	452	90	29	1	6.07	0.21
Connecticut	3,574,097	448	125	39	2	8.16	0.42
Delaware	900,877	105	117	0	0	0.00	0.00
Florida	18,801,310	1686	90	181	0	37.87	0.00
Georgia	9,687,653	943	97	31	0	6.49	0.00
Hawaii	1,360,301	0	0	16	1	3.35	0.21
Idaho	1,567,582	0	0	19	0	3.98	0.00
Illinois	12,830,632	1446	113	123	1	25.73	0.21
Indiana	6,483,802	644	99	13	0	2.72	0.00
Iowa	3,046,355	322	106	21	0	4.39	0.00
Kansas	2,853,118	369	129	13	0	2.72	0.00
Kentucky	4,339,367	517	119	0	0	0.00	0.00
Louisiana	4,533,372	644	142	12	0	2.51	0.00
Maine	1,328,361	189	142	0	0	0.00	0.00
Maryland	5,773,552	953	165	118	0	24.69	0.00
Massachusetts	6,547,629	952	145	41	1	8.58	0.21
Michigan	9,883,640	1323	134	249	4	52.09	0.84
Minnesota	5,303,925	585	110	41	0	8.58	0.00
Mississippi	2,967,297	421	142	0	0	0.00	0.00
Missouri	5,988,927	597	100	28	1	5.86	0.21
Montana	989,415	173	175	0	0	0.00	0.00
Nebraska	1,826,341	248	136	0	0	0.00	0.00
Nevada	2,700,551	185	69	6	2	1.26	0.42
New Hampshire	1,316,470	183	139	15	0	3.14	0.00
New Jersey	8,791,894	1627	185	51	0	10.67	0.00
New Mexico	2,059,179	309	150	4	0	0.84	0.00
New York	19,378,102	2236	115	89	9	18.62	1.88
North Carolina	9,535,483	1097	115	109	0	22.80	0.00
North Dakota	672,591	158	235	0	1	0.00	0.21
Ohio	11,536,504	1504	130	31	1	6.49	0.21
Oklahoma	3,751,351	367	98	0	0	0.00	0.00

Oregon	3,831,074	420	110	303	0	63.39	0.00
Pennsylvania	12,702,379	1525	120	22	2	4.60	0.42
Rhode Island	1,052,567	132	125	2	0	0.42	0.00
South Carolina	4,625,364	449	97	67	2	14.02	0.42
South Dakota	814,180	135	166	0	0	0.00	0.00
Tennessee	6,346,105	721	114	37	0	7.74	0.00
Texas	25,145,561	2590	103	184	1	38.50	0.21
Utah	2,763,885	180	65	11	0	2.30	0.00
Vermont	625,741	135	216	6	1	1.26	0.21
Virginia	8,001,024	1239	155	45	1	9.41	0.21
Washington	6,724,540	610	91	322	0	67.37	0.00
West Virginia	1,852,994	349	188	6	1	1.26	0.21
Wisconsin	5,686,986	766	135	29	0	6.07	0.00

Table E2.Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State, Year-to-Date through May 2011 and 2010 ($cents/kWh)

	Residential		All Sectors	
	2011	2010	2011	2010
New England	**16.01**	**16.62**	**14.56**	**15.03**
Connecticut	18.04	19.42	16.46	17.57
Maine	15.56	15.62	12.84	12.85
Massachusetts	14.73	15.44	14.01	14.51
New Hampshire	16.49	15.97	14.91	14.57
Rhode Island	15.69	15.89	13.73	14.25
Vermont	16.1	15.34	13.76	13.11
Middle Atlantic	**15.41**	**15.24**	**13.11**	**13.12**
New Jersey	16.34	15.93	14.2	14.07
New York	17.64	18.12	15.47	15.75
Pennsylvania	13.01	12.45	10.38	10.22
East North Central	**11.32**	**10.92**	**8.99**	**8.82**
Illinois	11.46	10.9	8.75	8.78
Indiana	9.88	9.22	7.97	7.46
Michigan	12.55	12.01	10.07	9.73
Ohio	10.77	10.8	8.75	8.89
Wisconsin	12.78	12.29	9.97	9.45
West North Central	**9.43**	**8.79**	**7.82**	**7.32**
Iowa	10.01	9.65	7.26	7.08
Kansas	10.06	9.43	8.42	7.84
Minnesota	10.65	9.92	8.46	8
Missouri	8.92	8.02	7.67	6.9

	Residential		All Sectors	
	2011	**2010**	**2011**	**2010**
North Dakota	7.64	7.35	6.94	6.59
South Dakota	8.61	8.28	7.71	7.41
South Atlantic	**11.05**	**10.71**	**9.64**	**9.41**
Delaware	13.57	13.37	11.7	11.73
District of Columbia	13.8	13.25	13.18	13.48
Florida	11.65	11.09	10.77	10.28
Georgia	10.53	9.64	9.23	8.56
Maryland	13.74	14.39	12.31	12.67
North Carolina	10.05	10.05	8.46	8.57
South Carolina	11.07	10.22	8.66	8.18
Virginia	10.12	10.33	8.53	8.7
West Virginia	9.09	8.47	7.72	7.28
East South Central	**9.95**	**9.15**	**8.32**	**7.74**
Alabama	10.91	10.47	8.82	8.6
Kentucky	8.98	8.12	6.98	6.32
Mississippi	10.27	9.61	8.74	8.33
Tennessee	9.72	8.64	8.92	8.08
West South Central	**10.33**	**10.54**	**8.39**	**8.68**
Arkansas	8.34	8.74	6.88	7.25
Louisiana	8.58	8.72	7.4	7.76
Oklahoma	8.96	8.56	7.26	6.94
Texas	11.24	11.59	9.02	9.39
Mountain	**10.06**	**10.01**	**8.19**	**8.2**
Arizona	10.55	10.29	9.17	9.03

	Residential			All Sectors
	2011	2010	2011	2010
Colorado	10.73	10.78	8.93	8.92
Idaho	7.86	7.79	6.52	6.52
Montana	9.38	8.74	8.09	7.63
Nevada	11.91	12.71	8.52	9.4
New Mexico	10.19	10	8.2	8.13
Utah	8.43	8.35	6.65	6.63
Wyoming	8.67	8.37	6.45	6.14
Pacific Contiguous	**12.09**	**12.08**	**10.81**	**10.66**
California	14.93	15.09	12.97	12.96
Oregon	9.34	8.67	8.07	7.58
Washington	8.09	7.76	7.09	6.57
Pacific Noncontiguous	**25.49**	**22.6**	**23.73**	**20.66**
Alaska	17.1	16.26	15.82	14.76
Hawaii	32.05	27.46	28.94	24.58
U.S. Total	**11.47**	**11.2**	**9.7**	**9.55**

Table E3. Metropolitan Statistical Areas by Population

Rank	Metropolitan Statistical Area	2010	2000
1	New York-Northern New Jersey-Long Island, NY-NJ-PA MSA	18,897,109	18,323,002
2	Los Angeles-Long Beach-Santa Ana, CA MSA	12,828,837	12,365,627
3	Chicago-Joliet-Naperville, IL-IN-WI MSA	9,461,105	9,098,316
4	Dallas-Fort Worth-Arlington, TX MSA	6,371,773	5,161,544
5	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD MSA	5,965,343	5,687,147
6	Houston-Sugar Land-Baytown, TX MSA	5,946,800	4,715,407
7	Washington-Arlington-Alexandria, DC-VA-MD-WV MSA	5,582,170	4,796,183
8	Miami-Fort Lauderdale-Pompano Beach, FL MSA	5,564,635	5,007,564
9	Atlanta-Sandy Springs-Marietta, GA MSA	5,268,860	4,247,981
10	Boston-Cambridge-Quincy, MA-NH MSA	4,552,402	4,391,344
11	San Francisco-Oakland-Fremont, CA MSA	4,335,391	4,123,740
12	Detroit-Warren-Livonia, MI MSA	4,296,250	4,452,557
13	Riverside-San Bernardino-Ontario, CA MSA	4,224,851	3,254,821
14	Phoenix-Mesa-Glendale, AZ MSA	4,192,887	3,251,876
15	Seattle-Tacoma-Bellevue, WA MSA	3,439,809	3,043,878
16	Minneapolis-St. Paul-Bloomington, MN-WI MSA	3,279,833	2,968,806
17	San Diego-Carlsbad-San Marcos, CA MSA	3,095,313	2,813,833
18	St. Louis, MO-IL MSA	2,812,896	2,698,687
19	Tampa-St. Petersburg-Clearwater, FL MSA	2,783,243	2,395,997
20	Baltimore-Towson, MD MSA	2,710,489	2,552,994
21	Denver-Aurora-Broomfield, CO MSA	2,543,482	2,179,240
22	Pittsburgh, PA MSA	2,356,285	2,431,087
23	Portland-Vancouver-Hillsboro, OR-WA MSA	2,226,009	1,927,881
24	Sacramento–Arden-Arcade–Roseville, CA MSA	2,149,127	1,796,857
25	San Antonio-New Braunfels, TX MSA	2,142,508	1,711,703
26	Orlando-Kissimmee-Sanford, FL MSA	2,134,411	1,644,561
27	Cincinnati-Middletown, OH-KY-IN MSA	2,130,151	2,009,632
28	Cleveland-Elyria-Mentor, OH MSA	2,077,240	2,148,143
29	Kansas City, MO-KS MSA	2,035,334	1,836,038
30	Las Vegas-Paradise, NV MSA	1,951,269	1,375,765

Rank	Metropolitan Statistical Area	2010	2000
31	San Jose-Sunnyvale-Santa Clara, CA MSA	1,836,911	1,735,819
32	Columbus, OH MSA	1,836,536	1,612,694
33	Charlotte-Gastonia-Rock Hill, NC-SC MSA	1,758,038	1,330,448
34	Indianapolis-Carmel, IN MSA	1,756,241	1,525,104
35	Austin-Round Rock-San Marcos, TX MSA	1,716,289	1,249,763
36	Virginia Beach-Norfolk-Newport News, VA-NC MSA	1,671,683	1,576,370
37	Providence-New Bedford-Fall River, RI-MA MSA	1,600,852	1,582,997
38	Nashville-Davidson–Murfreesboro–Franklin, TN MSA	1,589,934	1,311,789
39	Milwaukee-Waukesha-West Allis, WI MSA	1,555,908	1,500,741
40	Jacksonville, FL MSA	1,345,596	1,122,750
41	Memphis, TN-MS-AR MSA	1,316,100	1,205,204
42	Louisville/Jefferson County, KY-IN MSA	1,283,566	1,161,975
43	Richmond, VA MSA	1,258,251	1,096,957
44	Oklahoma City, OK MSA	1,252,987	1,095,421
45	Hartford-West Hartford-East Hartford, CT MSA	1,212,381	1,148,618
46	New Orleans-Metairie-Kenner, LA MSA	1,167,764	1,316,510
47	Buffalo-Niagara Falls, NY MSA	1,135,509	1,170,111
48	Raleigh-Cary, NC MSA	1,130,490	797,071
49	Birmingham-Hoover, AL MSA	1,128,047	1,052,238
50	Salt Lake City, UT MSA	1,124,197	968,858
51	Rochester, NY MSA	1,054,323	1,037,831
52	Tucson, AZ MSA	980,263	843,746
53	Honolulu, HI MSA	953,207	876,156
54	Tulsa, OK MSA	937,478	859,532
55	Fresno, CA MSA	930,450	799,407
56	Bridgeport-Stamford-Norwalk, CT MSA	916,829	882,567
57	Albuquerque, NM MSA	887,077	729,649
58	Albany-Schenectady-Troy, NY MSA	870,716	825,875
59	Omaha-Council Bluffs, NE-IA MSA	865,350	767,041
60	New Haven-Milford, CT MSA	862,477	824,008
61	Dayton, OH MSA	841,502	848,153
62	Bakersfield-Delano, CA MSA	839,631	661,645
63	Oxnard-Thousand Oaks-Ventura, CA MSA	823,318	753,197

Rank	Metropolitan Statistical Area	2010	2000
64	Allentown-Bethlehem-Easton, PA-NJ MSA	821,173	740,395
65	Baton Rouge, LA MSA	802,484	705,973
66	El Paso, TX MSA	800,647	679,622
67	Worcester, MA MSA	798,552	750,963
68	McAllen-Edinburg-Mission, TX MSA	774,769	569,463
69	Grand Rapids-Wyoming, MI MSA	774,160	740,482
70	Columbia, SC MSA	767,598	647,158
71	Greensboro-High Point, NC MSA	723,801	643,430
72	Akron, OH MSA	703,200	694,960
73	North Port-Bradenton-Sarasota, FL MSA	702,281	589,959
74	Little Rock-North Little Rock-Conway, AR MSA	699,757	610,518
75	Knoxville, TN MSA	698,030	616,079
76	Springfield, MA MSA	692,942	680,014
77	Stockton, CA MSA	685,306	563,598
78	Poughkeepsie-Newburgh-Middletown, NY MSA	670,301	621,517
79	Charleston-North Charleston-Summerville, SC MSA	664,607	549,033
80	Syracuse, NY MSA	662,577	650,154
81	Toledo, OH MSA	651,429	659,188
82	Colorado Springs, CO MSA	645,613	537,484
83	Greenville-Mauldin-Easley, SC MSA	636,986	559,940
84	Wichita, KS MSA	623,061	571,166
85	Cape Coral-Fort Myers, FL MSA	618,754	440,888
86	Boise City-Nampa, ID MSA	616,561	464,840
87	Lakeland-Winter Haven, FL MSA	602,095	483,924
88	Des Moines-West Des Moines, IA MSA	569,633	481,394
89	Madison, WI MSA	568,593	501,774
90	Youngstown-Warren-Boardman, OH-PA MSA	565,773	602,964
91	Scranton–Wilkes-Barre, PA MSA	563,631	560,625
92	Augusta-Richmond County, GA-SC MSA	556,877	499,684
93	Harrisburg-Carlisle, PA MSA	549,475	509,074
94	Ogden-Clearfield, UT MSA	547,184	442,656
95	Palm Bay-Melbourne-Titusville, FL MSA	543,376	476,230
96	Jackson, MS MSA	539,057	497,197
97	Chattanooga, TN-GA MSA	528,143	476,531
98	Provo-Orem, UT MSA	526,810	376,774
99	Lancaster, PA MSA	519,445	470,658
100	Modesto, CA MSA	514,453	446,997

Rank	Metropolitan Statistical Area	2010	2000
101	Portland-South Portland-Biddeford, ME MSA	514,098	487,568
102	Durham-Chapel Hill, NC MSA	504,357	426,493
103	Deltona-Daytona Beach-Ormond Beach, FL MSA	494,593	443,343
104	Santa Rosa-Petaluma, CA MSA	483,878	458,614
105	Winston-Salem, NC MSA	477,717	421,961
106	Lexington-Fayette, KY MSA	472,099	408,326
107	Spokane, WA MSA	471,221	417,939
108	Lansing-East Lansing, MI MSA	464,036	447,728
109	Fayetteville-Springdale-Rogers, AR-MO MSA	463,204	347,045
110	Pensacola-Ferry Pass-Brent, FL MSA	448,991	412,153
111	Visalia-Porterville, CA MSA	442,179	368,021
112	Springfield, MO MSA	436,712	368,374
113	York-Hanover, PA MSA	434,972	381,751
114	Corpus Christi, TX MSA	428,185	403,280
115	Flint, MI MSA	425,790	436,141
116	Reno-Sparks, NV MSA	425,417	342,885
117	Asheville, NC MSA	424,858	369,171
118	Port St. Lucie, FL MSA	424,107	319,426
119	Santa Barbara-Santa Maria-Goleta, CA MSA	423,895	399,347
120	Huntsville, AL MSA	417,593	342,376
121	Fort Wayne, IN MSA	416,257	390,156
122	Salinas, CA MSA	415,057	401,762
123	Vallejo-Fairfield, CA MSA	413,344	394,542
124	Mobile, AL MSA	412,992	399,843
125	Reading, PA MSA	411,442	373,638
126	Brownsville-Harlingen, TX MSA	406,220	335,227
127	Killeen-Temple-Fort Hood, TX MSA	405,300	330,714
128	Canton-Massillon, OH MSA	404,422	406,934
129	Manchester-Nashua, NH MSA	400,721	380,841
130	Shreveport-Bossier City, LA MSA	398,604	375,965
131	Salem, OR MSA	390,738	347,214
132	Beaumont-Port Arthur, TX MSA	388,745	385,090
133	Anchorage, AK MSA	380,821	319,605
134	Davenport-Moline-Rock Island, IA-IL MSA	379,690	376,019
135	Peoria, IL MSA	379,186	366,899
136	Montgomery, AL MSA	374,536	346,528
137	Tallahassee, FL MSA	367,413	320,304
138	Trenton-Ewing, NJ MSA	366,513	350,761

Rank	Metropolitan Statistical Area	2010	2000
139	Fayetteville, NC MSA	366,383	336,609
140	Hickory-Lenoir-Morganton, NC MSA	365,497	341,851
141	Wilmington, NC MSA	362,315	274,532
142	Evansville, IN-KY MSA	358,676	342,815
143	Eugene-Springfield, OR MSA	351,715	322,959
144	Rockford, IL MSA	349,431	320,204
145	Savannah, GA MSA	347,611	293,000
146	Ann Arbor, MI MSA	344,791	322,895
147	Ocala, FL MSA	331,298	258,916
148	Kalamazoo-Portage, MI MSA	326,589	314,866
149	Naples-Marco Island, FL MSA	321,520	251,377
150	South Bend-Mishawaka, IN-MI MSA	319,224	316,663
151	Kingsport-Bristol-Bristol, TN-VA MSA	309,544	298,484
152	Roanoke, VA MSA	308,707	288,309
153	Green Bay, WI MSA	306,241	282,599
154	Charleston, WV MSA	304,284	309,635
155	Lincoln, NE MSA	302,157	266,787
156	Fort Collins-Loveland, CO MSA	299,630	251,494
157	Utica-Rome, NY MSA	299,397	299,896
158	Fort Smith, AR-OK MSA	298,592	273,170
159	Columbus, GA-AL MSA	294,865	281,768
160	Boulder, CO MSA	294,567	269,814
151	Huntington-Ashland, WV-KY-OH MSA	287,702	288,649
162	Lubbock, TX MSA	284,890	249,700
163	Spartanburg, SC MSA	284,307	253,791
164	Erie, PA MSA	280,566	280,843
165	Duluth, MN-WI MSA	279,771	275,486
166	Atlantic City-Hammonton, NJ MSA	274,549	252,552
167	Norwich-New London, CT MSA	274,055	259,088
168	Clarksville, TN-KY MSA	273,949	232,000
169	Lafayette, LA MSA	273,738	239,086
170	San Luis Obispo-Paso Robles, CA MSA	269,637	246,681
171	Myrtle Beach-North Myrtle Beach-Conway, SC MSA	269,291	196,629
172	Hagerstown-Martinsburg, MD-WV MSA	269,140	222,771
173	Gainesville, FL MSA	264,275	232,392
174	Holland-Grand Haven, MI MSA	263,801	238,314
175	Santa Cruz-Watsonville, CA MSA	262,382	255,602
176	Cedar Rapids, IA MSA	257,940	237,230
177	Merced, CA MSA	255,793	210,554
178	Kennewick-Pasco-Richland, WA MSA	253,340	191,822
179	Greeley, CO MSA	252,825	180,926

Rank	Metropolitan Statistical Area	2010	2000
180	Lynchburg, VA MSA	252,634	228,616
181	Olympia, WA MSA	252,264	207,355
182	Binghamton, NY MSA	251,725	252,320
183	Bremerton-Silverdale, WA MSA	251,133	231,969
184	Laredo, TX MSA	250,304	193,117
185	Amarillo, TX MSA	249,881	226,522
186	Gulfport-Biloxi, MS MSA	248,820	246,190
187	Yakima, WA MSA	243,231	222,581
188	Waco, TX MSA	234,906	213,517
189	Topeka, KS MSA	233,870	224,551
190	Macon, GA MSA	232,293	222,368
191	Champaign-Urbana, IL MSA	231,891	210,275
192	College Station-Bryan, TX MSA	228,660	184,885
193	Sioux Falls, SD MSA	228,261	187,093
194	Appleton, WI MSA	225,666	201,602
195	Chico, CA MSA	220,000	203,171
196	Tuscaloosa, AL MSA	219,461	192,034
197	Barnstable Town, MA MSA	215,888	222,230
198	Longview, TX MSA	214,369	194,042
199	Burlington-South Burlington, VT MSA	211,261	198,889
200	Prescott, AZ MSA	211,033	167,517
201	Springfield, IL MSA	210,170	201,437
202	Tyler, TX MSA	209,714	174,706
203	Las Cruces, NM MSA	209,223	174,682
204	Fargo, ND-MN MSA	208,777	174,367
205	Houma-Bayou Cane-Thibodaux, LA MSA	208,178	194,477
206	Florence, SC MSA	205,566	193,155
207	Medford, OR MSA	203,206	181,269
208	Lafayette, IN MSA	201,789	178,541
209	Charlottesville, VA MSA	201,559	174,021
210	Bellingham, WA MSA	201,140	166,814
211	Lake Havasu City-Kingman, AZ MSA	200,186	155,032
212	Saginaw-Saginaw Township North, MI MSA	200,169	210,039
213	Lake Charles, LA MSA	199,607	193,568
214	Johnson City, TN MSA	198,716	181,607
215	Elkhart-Goshen, IN MSA	197,559	182,791
216	Yuma, AZ MSA	195,751	160,026
217	Racine, WI MSA	195,408	188,831
218	Bloomington, IN MSA	192,714	175,506
219	Athens-Clarke County, GA MSA	192,541	166,079
220	Greenville, NC MSA	189,510	152,772

Rank	Metropolitan Statistical Area	2010	2000
221	St. Cloud, MN MSA	189,093	167,392
222	Anderson, SC MSA	187,126	165,740
223	Rochester, MN MSA	186,011	163,618
224	Kingston, NY MSA	182,493	177,749
225	Crestview-Fort Walton Beach-Destin, FL MSA	180,822	170,498
226	Gainesville, GA MSA	179,684	139,277
227	Jacksonville, NC MSA	177,772	150,355
228	Redding, CA MSA	177,223	163,256
229	Monroe, LA MSA	176,441	170,053
230	Joplin, MO MSA	175,518	157,322
231	El Centro, CA MSA	174,528	142,361
232	Columbia, MO MSA	172,786	145,666
233	Terre Haute, IN MSA	172,425	170,943
234	Muskegon-Norton Shores, MI MSA	172,188	170,200
235	Bloomington-Normal, IL MSA	169,572	150,433
236	Panama City-Lynn Haven-Panama City Beach, FL MSA	168,852	148,217
237	Waterloo-Cedar Falls, IA MSA	167,819	163,706
238	Oshkosh-Neenah, WI MSA	166,994	156,763
239	Yuba City, CA MSA	166,892	139,149
240	Abilene, TX MSA	165,252	160,245
241	Blacksburg-Christiansburg-Radford, VA MSA	162,958	151,272
242	Dover, DE MSA	162,310	126,697
243	Pascagoula, MS MSA	162,246	150,564
244	Parkersburg-Marietta-Vienna, WV-OH MSA	162,056	164,624
245	Eau Claire, WI MSA	161,151	148,337
246	Janesville, WI MSA	160,331	152,307
247	Jackson, MI MSA	160,248	158,422
248	Punta Gorda, FL MSA	159,978	141,627
249	Pueblo, CO MSA	159,063	141,472
250	Billings, MT MSA	158,050	138,904
251	Bend, OR MSA	157,733	115,367
252	Albany, GA MSA	157,308	157,833
253	Vineland-Millville-Bridgeton, NJ MSA	156,898	146,438
254	Niles-Benton Harbor, MI MSA	156,813	162,453
255	State College, PA MSA	153,990	135,758
256	Bangor, ME MSA	153,923	144,919
257	Alexandria, LA MSA	153,922	145,035
258	Decatur, AL MSA	153,829	145,867
259	Hanford-Corcoran, CA MSA	152,982	129,461

Rank	Metropolitan Statistical Area	2010	2000
260	Iowa City, IA MSA	152,586	131,676
261	Rocky Mount, NC MSA	152,392	143,026
262	Monroe, MI MSA	152,021	145,945
263	Wichita Falls, TX MSA	151,306	151,524
264	Burlington, NC MSA	151,131	130,800
265	Madera-Chowchilla, CA MSA	150,865	123,109
266	Jefferson City, MO MSA	149,807	140,052
267	Wheeling, WV-OH MSA	147,950	153,172
268	Florence-Muscle Shoals, AL MSA	147,137	142,950
269	Grand Junction, CO MSA	146,723	116,255
270	Dothan, AL MSA	145,639	130,861
271	Santa Fe, NM MSA	144,170	129,292
272	Johnstown, PA MSA	143,679	152,598
273	Sioux City, IA-NE-SD MSA	143,577	143,053
274	Hattiesburg, MS MSA	142,842	123,812
275	Dalton, GA MSA	142,227	120,031
276	Auburn-Opelika, AL MSA	140,247	115,092
277	Warner Robins, GA MSA	139,900	110,765
278	Valdosta, GA MSA	139,588	119,560
279	Coeur d'Alene, ID MSA	138,494	108,685
280	Springfield, OH MSA	138,333	144,742
281	St. George, UT MSA	138,115	90,354
282	Sebastian-Vero Beach, FL MSA	138,028	112,947
283	Odessa, TX MSA	137,130	121,123
284	Midland, TX MSA	136,872	116,009
285	Morristown, TN MSA	136,608	123,081
286	Napa, CA MSA	136,484	124,279
287	Battle Creek, MI MSA	136,146	137,985
288	Texarkana, TX-Texarkana, AR MSA	136,027	129,749
289	Flagstaff, AZ MSA	134,421	116,320
290	Wausau, WI MSA	134,063	125,834
291	La Crosse, WI-MN MSA	133,665	126,838
292	Lebanon, PA MSA	133,568	120,327
293	Anderson, IN MSA	131,636	133,358
294	Pittsfield, MA MSA	131,219	134,953
295	Idaho Falls, ID MSA	130,374	101,677
296	Farmington, NM MSA	130,044	113,801
297	Morgantown, WV MSA	129,709	111,200
298	Glens Falls, NY MSA	128,923	124,345
299	Winchester, VA-WV MSA	128,472	102,997
300	St. Joseph, MO-KS MSA	127,329	122,336
301	Altoona, PA MSA	127,089	129,144

Rank	Metropolitan Statistical Area	2010	2000
302	Manhattan, KS MSA	127,081	108,999
303	Rapid City, SD MSA	126,382	112,818
304	Bowling Green, KY MSA	125,953	104,166
305	Logan, UT-ID MSA	125,442	102,720
306	Harrisonburg, VA MSA	125,228	108,193
307	Salisbury, MD MSA	125,203	109,391
308	Mansfield, OH MSA	124,475	128,852
309	Steubenville-Weirton, OH-WV MSA	124,454	132,008
310	Lawton, OK MSA	124,098	114,996
311	Goldsboro, NC MSA	122,623	113,329
312	Jonesboro, AR MSA	121,026	107,762
313	Sherman-Denison, TX MSA	120,877	110,595
314	Elizabethtown, KY MSA	119,736	107,547
315	Anniston-Oxford, AL MSA	118,572	112,249
316	Muncie, IN MSA	117,671	118,769
317	Mount Vernon-Anacortes, WA MSA	116,901	102,979
318	Williamsport, PA MSA	116,111	120,044
319	Cleveland, TN MSA	115,788	104,015
320	Sheboygan, WI MSA	115,507	112,646
321	Jackson, TN MSA	115,425	107,377
322	Victoria, TX MSA	115,384	111,663
323	Owensboro, KY MSA	114,752	109,875
324	Kankakee-Bradley, IL MSA	113,449	103,833
325	Brunswick, GA MSA	112,370	93,044
326	San Angelo, TX MSA	111,823	105,781
327	Michigan City-La Porte, IN MSA	111,467	110,106
328	Wenatchee-East Wenatchee, WA MSA	110,884	99,219
329	Lawrence, KS MSA	110,826	99,962
330	Decatur, IL MSA	110,768	114,706
331	Missoula, MT MSA	109,299	95,802
332	Bismarck, ND MSA	108,779	94,719
333	Bay City, MI MSA	107,771	110,157
334	Lewiston-Auburn, ME MSA	107,702	103,793
335	Sumter, SC MSA	107,456	104,646
336	Danville, VA MSA	106,561	110,156
337	Lima, OH MSA	106,331	108,473
338	Gadsden, AL MSA	104,430	103,459
339	Cumberland, MD-WV MSA	103,299	102,008
340	Longview, WA MSA	102,410	92,948
341	Fond du Lac, WI MSA	101,633	97,296
342	Ithaca, NY MSA	101,564	96,501
343	Pine Bluff, AR MSA	100,258	107,341

Rank	Metropolitan Statistical Area	2010	2000
344	Kokomo, IN MSA	98,688	101,541
345	Grand Forks, ND-MN MSA	98,461	97,478
346	Fairbanks, AK MSA	97,581	82,840
347	Ocean City, NJ MSA	97,265	102,326
348	Mankato-North Mankato, MN MSA	96,740	85,712
349	Rome, GA MSA	96,317	90,565
350	Cape Girardeau-Jackson, MO-IL MSA	96,275	90,312
351	Hot Springs, AR MSA	96,024	88,068
352	Palm Coast, FL MSA	95,696	49,832
353	Dubuque, IA MSA	93,653	89,143
354	Cheyenne, WY MSA	91,738	81,607
355	Pocatello, ID MSA	90,656	83,103
356	Ames, IA MSA	89,542	79,981
357	Elmira, NY MSA	88,830	91,070
358	Corvallis, OR MSA	85,579	78,153
359	Danville, IL MSA	81,625	83,919
360	Great Falls, MT MSA	81,327	80,357
361	Hinesville-Fort Stewart, GA MSA	77,917	71,914
362	Sandusky, OH MSA	77,079	79,551
363	Columbus, IN MSA	76,794	71,435
364	Casper, WY MSA	75,450	66,533
365	Lewiston, ID-WA MSA	60,888	57,961
366	Carson City, NV MSA	55,274	52,457

Table E4.Parking Costs per Market (United States Metropolitan Statistical Areas)

		MARKET	HIGH	LOW	MEDIAN
1	Phoenix,	AZ	$65.0	$25.0	$40.0
2	Reno,	NV	$55.0	$30.0	$45.0
3	Walnut	Creek,	$65.0	$30.0	$47.5
4	Ft.	Lauderdale,	$63.6	$26.5	$53.0
5	Bakersfield,	CA	$65.0	$45.0	$55.0
6	Memphis,	TN	$90.0	$20.0	$57.0
7	Little	Rock,	$80.6	$52.7	$59.1
8	Columbia,	SC	$90.0	$40.0	$65.0
9	Fresno,	CA	$95.0	$50.0	$65.0
10	Las	Vegas,	$65.0	$65.0	$65.0
11	West	Palm	$85.0	$68.9	$68.9
12	Greenville,	SC	$69.7	$69.7	$69.7
13	Boise,	ID	$90.0	$80.0	$80.0
14	Savannah,	GA	$100.0	$35.0	$80.0
15	Dallas,	TX	$155.0	$40.0	$85.0
16	Orlando,	FL	$150.0	$55.0	$87.5
17	Atlanta,	GA	$135.0	$35.0	$93.0
18	Jacksonville,	FL	$125.0	$85.6	$95.5
19	San	Jose/Silicon	$165.0	$75.0	$100.0
20	Charleston,	SC	$120.0	$110.0	$110.0
21	Indianapolis,	IN	$165.0	$80.0	$115.0
22	Columbus,	OH	$190.0	$75.0	$125.0
23	Tampa,	FL	$150.0	$110.0	$135.0
24	Houston,	TX	$250.0	$60.0	$146.0
25	Cincinnati,	OH	$225.0	$85.0	$150.0
26	Miami,	FL	$250.0	$127.4	$150.0
27	Cleveland,	OH	$220.0	$95.0	$155.0
28	Bellevue,	WA	$200.0	$132.0	$162.0
29	San	Diego,	$190.0	$150.0	$170.0
30	Denver,	CO	$195.0	$165.0	$175.0
31	Hartford,	CT	$210.0	$100.0	$175.0
32	Portland,	OR	$210.0	$165.0	$185.0
33	Oakland,	CA	$230.0	$135.6	$195.0
34	Sacramento,	CA	$325.0	$145.0	$200.0
35	Los	Angeles,	$363.0	$100.0	$210.0
36	Honolulu,	HI	$325.0	$100.0	$222.3
37	Washington,	DC	$290.0	$200.0	$245.0
38	Seattle,	WA	$353.9	$216.0	$285.0
39	Philadelphia,	PA	$464.0	$175.0	$300.0
40	Chicago,	IL	$515.0	$195.0	$320.0
41	San	Francisco,	$550.0	$160.0	$375.0
42	Boston,	MA	$500.0	$375.0	$425.0
43	New	York,	$800.0	$265.0	$529.0
44	New	York,	$1,200.0	$296.0	$538.0