INCORPORATING SUSTAINABILITY INTO TRANSPORTATION PLANNING AND DECISION MAKING:

DEFINITIONS, PERFORMANCE MEASURES, AND EVALUATION

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INCORPORATING SUSTAINABILITY INTO TRANSPORTATION PLANNING AND DECISION MAKING:

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To my parents

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SUMMARY

An increasing number of agencies have begun to define "sustainability" for transportation systems and are taking steps to incorporate the concept into the regional transportation planning process. Planning for sustainable transportation systems should at the very least incorporate their broader impacts on system effectiveness, environmental integrity, economic development, and the social quality of life. This study reviews definitions, performance measures, and evaluation methodologies for transportation system sustainability and demonstrates a framework for incorporating sustainability considerations in transportation planning and decision making. Through a case study using data from the Atlanta Metropolitan Region, the study evaluates competing transportation and land use plans based on a broad range of sustainability parameters using relevant spatial and environmental analyses. A multiple criteria decision making (MCDM) method enables the aggregation of individual performance measures into four basic indexes and further into a composite sustainability index based on regional goals and priorities. The value of the indexes lies in their ability to capture the multidimensional nature of sustainability as well as important tradeoffs among the potentially conflicting decision criteria. A decision support tool is proposed to visualize dominance and tradeoffs when evaluating alternatives and to effectively reflect changing regional priorities over time. The proposed framework should help decision makers with incorporating sustainability considerations into transportation planning as well as identifying superior plans for predetermined objectives.

CHAPTER 1

INTRODUCTION

1.1. Background

Identified as a global priority by the United Nations in the early 1980s, the concept of sustainable development is most commonly defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987). This concept has permeated many areas of engineering, including transportation systems engineering. As evidence, a growing number of agencies have begun to define "sustainability" for transportation systems and are attempting to incorporate the concept into the regional transportation planning process (Jeon et al. 2007). Considering a broader definition of transportation sustainability as improving the overall quality of life, and not just enhancing transportation systems, mission statements of more than twenty State Departments of Transportation (DOTs) in the United States now include sustainability either explicitly or implicitly (Jeon and Amekudzi, 2005). Table 1 shows how these missions capture the concept of sustainability, culled from a search of DOT websites for 50 states and the District of Columbia. The Georgia DOT, for example, "strives to provide a safe, seamless, and sustainable transportation system that supports Georgia's economy and is sensitive to its citizens and environment." Accordingly, major organizations such as the Organization for Cooperation and Economic Development (OECD) and the Center for Sustainable Transportation (CST) of Canada have adopted definitions for sustainable transportation. Jeon and Amekudzi (2005) reviewed sixteen practitioner and research initiatives on sustainability to distill

Table 1 Sustainability in the Missions of State Departments of Transportation (U. S.)

Departments/States	Mission Statement
U.S. Department of Transportation (Sep. 21. 2007)	"Serve the United States by ensuring a fast, safe, efficient, accessible, and convenient transportation system that meets our vital national interests and enhances the quality of life of the American people, today and into the future." (http://www.dot.gov/mission.htm)
Alabama (New)	"To provide a safe, efficient, environmentally sound intermodal transportation system for all users, especially the taxpayers of Alabama. To also facilitate economic and social development and prosperity through the efficient movement of people and goods and to facilitate intermodal connections within Alabama." (http://www.dot.state.al.us/Public_Info/organization.asp#Mission:)
Florida (Sep. 21, 2007)	"The Department will provide a safe transportation system that ensures the mobility of people and goods, enhances economic prosperity and preserves the quality of our environment and communities." (http://www.dot.state.fl.us/publicinformationoffice/moreDOT/mvv.htm)
Georgia (Sep. 21, 2007)	"The Georgia Department of Transportation provides a safe, seamless, and sustainable transportation system that supports Georgia's economy and is sensitive to its citizens and environment." (http://www.dot.state.ga.us/specialsubjects/aboutgdot/index.shtml)
Hawaii (New)	"To provide a safe, efficient, accessible, and inter-modal transportation system that ensures the mobility of people and goods, and enhances and/or preserves economic prosperity and the quality of life." (http://www.hawaii.gov/dot/about.htm)
Indiana (Sep. 21, 2007)	"INDOT will build, maintain, and operate a superior transportation system enhancing safety, mobility and economic growth." (http://www.in.gov/dot/about/general/sp.html)
Louisiana (Updated, Sep. 21, 2007)	"To deliver transportation and public works systems that enhance quality of life and facilitate economic growth and recovery." (http://www.dotd.louisiana.gov/press/vision_mission_goals_3-27-06.pdf)
Michigan (Sep. 21, 2007)	"Providing the highest quality integrated transportation services for economic benefit and improved quality of life." (http://www.michigan.gov/mdot/0,1607,7-151-9623-65024--,00.html)
Montana (Sep. 21, 2007)	"Montana MDT's mission is to serve the public by providing a transportation system and services that emphasize quality, safety, cost effectiveness, economic vitality and sensitivity to the environment." (http://www.mdt.mt.gov/mdt/mission.shtml)
New Hampshire (New)	"To plan, construct, and maintain the best possible transportation system and State facilities in the most efficient, environmentally sensitive, and economical manner, utilizing quality management techniques consistent with available resources and mandated controls." (http://www.nh.gov/dot/)
New Jersey (June 26, 2007)	"Improving Lives by Improving Transportation." (http://www.state.nj.us/transportation/about/mission.shtm)
New York (Sep. 21, 2007)	"To ensure our customers -- those who live, work, and travel in New York State -- have a safe, efficient, balanced, and environmentally sound transportation system. (https://www.nysdot.gov/portal/page/portal/about-nysdot/mission)
Nevada (Sep. 21, 2007)	"To efficiently plan, design, construct and maintain a safe and effective transportation system for Nevada's travelers taking into consideration the environment, economic and social needs and intermodal transportation opportunities." (http://www.nevadadot.com/about/)
North Carolina (New)	"Connecting people and places in North Carolina – safely and efficiently, with accountability and environmental sensitivity." (http://www.ncdot.org/about/ncdot/mission.html)
Ohio (New)	"To provide a world-class transportation system that links Ohio to a global economy while preserving the state's unique character and enhancing its quality of life." (http://www.dot.state.oh.us/)
Oregon (Sep. 21, 2007)	"To provide a safe and efficient transportation system that supports economic opportunity and livable communities for Oregonians" (http://www.odot.state.or.us/06about.htm)

Table 1 continued

Departments/States	Mission Statement
Rhode Island (Sep. 21, 2007)	"To maintain and provide a safe, efficient, environmentally, aesthetically and culturally sensitive intermodal transportation network that offers a variety of convenient, cost-effective mobility opportunities for people and the movement of goods supporting economic development and improved quality of life." (http://www.dot.state.ri.us/WebOrgz/mission.htm)
South Dakota (Sep. 21, 2007)	"We provide a transportation system to satisfy diverse mobility needs in a cost effective manner while retaining concern for safety and the environment." (http://www.sddot.com/geninfo_org_mission.asp)
Texas (New)	"To work cooperatively to provide safe, effective, and efficient movement of people and goods." (http://www.dot.state.tx.us/about_us/mission.htm)
Utah (New)	"Quality Transportation Today, Better Transportation Tomorrow." (http://www.sr.ex.state.ut.us/main/f?p=100:pg:8578495294964822162:::1:T,V:33,)
Vermont (Updated, Sep. 21, 2007)	"To provide for the movement of people and commerce in a safe, reliable, cost-effective and environmentally responsible manner." (http://www.aot.state.vt.us/MissionVision.htm)
West Virginia (Sep. 21, 2007)	"To create and maintain for the people of West Virginia, the United States and the world a multi-modal and inter-modal transportation system that supports the safe, effective and efficient movement of people, information and goods that enhances the opportunity for people and communities to enjoy environmentally sensitive and economically sound development. (http://www.wvdot.com/11_WVDOT/11_about.htm)

Updated from Jeon and Amekudzi (2005).

the necessary parameters for sustainability evaluation. The Center for Sustainable Transportation Canada, for example, 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, reuses and recycles its components, and minimizes the use of land and the production of noise. While there is no standard definition of sustainable transportation, sustainability is largely captured in terms of transportation system effectiveness and system impact on economic productivity, environmental integrity, and the social quality of life (Jeon and

Amekudzi 2005). In fact, the latter three factors are commonly considered the essential dimensions of a sustainable transportation system (See Figure 1).

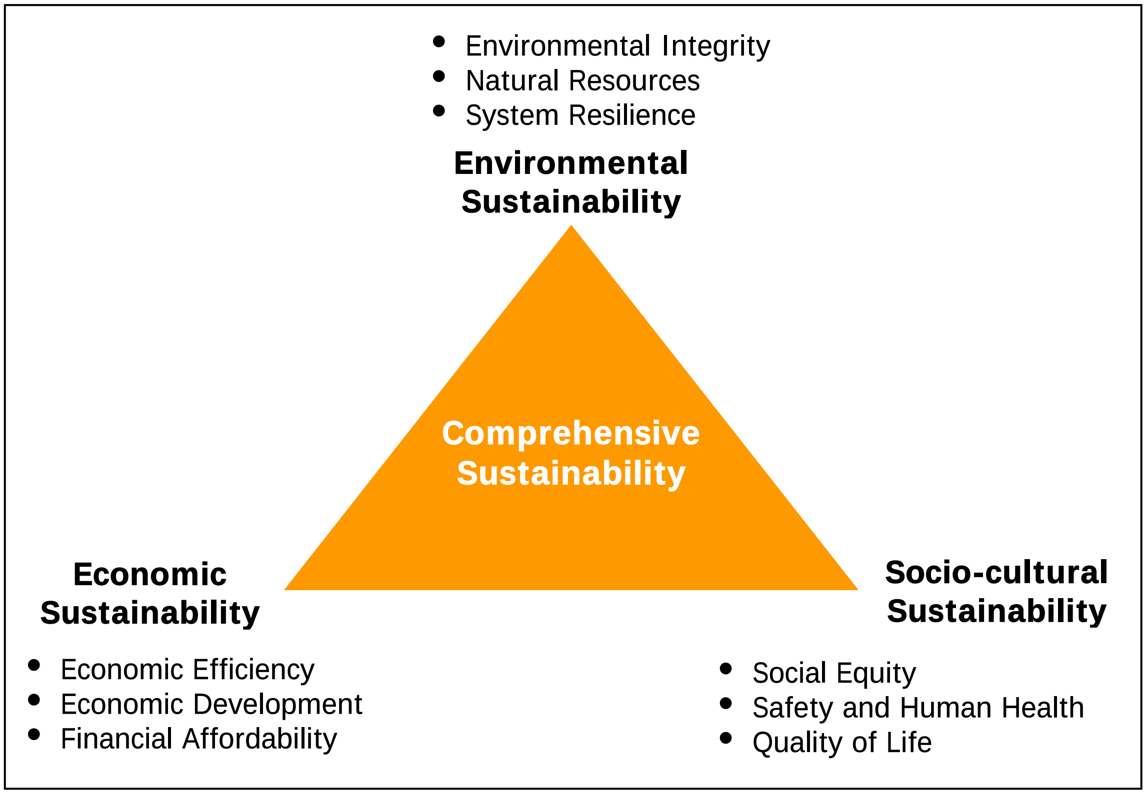


Figure 1 Three essential factors of transportation system sustainability

This study starts out by characterizing the emergent thinking on what constitutes transportation sustainability and how to measure it. Then, the study identifies some of the major transportation system sustainability issues in different countries depending on prevailing socioeconomic conditions and political/administrative institutions. Finally, the study focuses on demonstrating a feasible methodology for incorporating sustainability considerations into the planning process using data from the metropolitan Atlanta region.

1.2. Research Objectives

The fact that sustainability is an increasingly important issue in transportation system and services provision is evident in congested highway systems in urban areas, declining air quality and respiratory health; and the need for improved and more equitable access to basic social and economic services in several areas around the world (Jeon, Amekudzi et al. 2006). While about 40% of State DOTs have incorporated a range of sustainability goals into their missions, the state-of-the-practice of sustainability planning is far from perfect. In fact, very few metropolitan planning organizations (MPOs) attempt to quantify the overall impact of the transportation system and land use changes on the economy, environment, and social equity over time (i.e., the comprehensive concept of sustainability). Conventional evaluation of transportation plans, however, focuses mainly on performance measures pertaining to transportation system effectiveness as well as the adverse environmental impacts of the system with less of a focus on economic and social impacts (Jeon and Amekudzi, 2005). Transportation system effectiveness indicators such as congestion and vehicle miles traveled and environmental indicators (mainly air quality indicators) have been predominant performance measures for evaluating transportation plans.

The objective of this study is threefold. First, it is to determine the essential elements of transportation system sustainability and to investigate appropriate performance measures for evaluating sustainability. Second, it is to demonstrate a feasible methodology for evaluating competing transportation and land use plans based on a broad range of sustainability parameters (system performance, environmental impacts, economic development, social equity, and public health) using relevant spatial and environmental analyses. Third, it is to propose a decision support tool which enables decision makers to incorporate sustainability considerations in transportation planning as well as identify superior plans for predetermined regional objectives.

1.3. Research Methods

This research starts with an extensive literature review on definitions, performance measures, and evaluation methodologies for transportation system sustainability. The study then performs a comparative analysis of diverse sustainability issues in selected countries with different socioeconomic conditions. The study then evaluates the sustainability of selected transportation and land use scenarios using data for the Metropolitan Atlanta Region. A composite sustainability index (CSI), coupled with multiple criteria decision making (MCDM) methods, is introduced as a useful decision support tool for evaluating the sustainability of competing plans, and hence integrating sustainability in the regional transportation planning process.

1.3.1. Literature Review

First of all, a comprehensive literature review on sustainability and transportation systems was conducted to understand what the state-of-the-art is in the area and to determine the current definitions and performance measures being used to address transportation system sustainability. The first section of the literature review discusses the state of the practice on definitions and performance measures of sustainability by synthesizing national or international initiatives on sustainability measurement using indicator systems. The second section of the literature review identifies a number of emergent methodologies being used to evaluate sustainability in transportation systems planning and provision. The third section of the literature review explores the multiple criteria decision making

(MCDM) methodology which effectively captures the multidimensional nature of sustainability. Definitions, performance categories, and relevant applications of the MCDM methods in transportation planning and policy making were identified.

1.3.2. Case Study -- Sustainability Issues

While sustainable transportation is a policy objective or issue of concern around the world, critical priorities, standards, and constraints for attaining sustainability may be varied in different countries depending on prevailing socioeconomic conditions, political, and administrative institutions. Case studies were performed to characterize some of the major issues related to transportation sustainability in high-, middle-, and low-income economies. The four case studies were selected to capture a range of economic conditions: Georgia (United States, high-income status), South Korea (East Asia, recently moved from middle to high-income status), Colombia (South America, middle-income status) and Ghana (West Africa, low-income status). The studies showed that the urgent priorities for improving transportation system performance may be different in countries/regions with different socioeconomic conditions.

1.3.3. Evaluation of Sustainability in the Regional Planning Context

Based on the literature review and case studies, a framework that incorporates sustainability considerations into regional transportation planning was developed and applied to evaluate development scenarios using data from the Atlanta Metropolitan Region. First, pertinent sustainability issues and associated sustainability goals for the Atlanta region were identified. Second, relevant sustainability indicators were determined based on the regional sustainability issues and goals. The relative importance of the indicators was projected based on regional priorities, and an index introduced to capture the sustainability of alternative scenarios developed from multiple land use and transportation plans. Third, selected transportation and land use plans for the Atlanta region were evaluated using a range of sustainability parameters: environmental, economic, and social, in addition to transportation system effectiveness. An adopted regional transportation plan resulting from the traditional four-step travel demand modeling process was combined with selected future land use scenarios with the aid of Geographic Information System (GIS) and these integrated scenarios were evaluated to demonstrate the benefits of the methodology. A sensitivity analysis was performed by varying the weights or priorities of the different sustainability dimensions/indicators, which reflect relative priorities on the objectives from the regional sustainability vision and goals. The policy implications of the sustainability evaluation results are discussed including the tradeoffs associated with the scenarios.

1.4. Research Scope

The research utilizes qualitative data on regional goals, objectives, and performance measures and quantitative data supporting three transportation and land use scenarios from the Atlanta Metropolitan Region. The analysis area encompasses 1,683 traffic analysis zones (TAZs) and 13-county metropolitan area of Atlanta, Georgia. Three different scenarios were generated from multiple transportation and land use plan alternatives: (1) the Baseline 2005, (2) the Mobility 2030, and (3) the Test Case 2030 scenarios. The two future scenarios, the Mobility and Test Case scenarios are created by integrating an adopted Regional Transportation Plan (RTP) for the year 2030 with the two future land use scenarios, which are the Mobility 2030 and Draft Local Aspirations scenarios respectively. Both the transportation plan and land use scenarios are developed by the Atlanta Regional Commission (ARC), which is the metropolitan planning organization (MPO) of the Atlanta Metropolitan Region. The development of these land use scenarios is in line with the Envision 6 program, which ARC has launched for essentially integrating land use planning and transportation planning as it updates the Regional Transportation Plan (RTP). Therefore, these integrated scenarios are outcomes from interactive process based on a series of stakeholder meeting, regional charrette with various stakeholder, and web and telephone surveys(ARC, 2006). It is important to articulate clearly the limitations of the scenarios created for this study. The Test Case 2030 scenario used in this study is generated using interim data from ARC. The Test Case 2030 scenario was created by integrating the adopted regional transportation plan (RTP) for the year 2030 with an interim future land use scenario: the Draft Local Aspirations scenarios. At the point in the planning process when the data were obtained from the planning agency, the agency only possessed the two different future land use scenarios along with the previously adopted RTP transportation network volume data. The different land use patterns (development of new residential and work locations) in the two 2030 future scenarios must necessarily lead to different travel patterns, traffic volumes, and onroad operating conditions (congestion levels) even though the transportation network is assumed to remain unchanged. However, the modified transportation plan for the Local Aspirations land use scenario was not available during the period in which analyses were conducted for this dissertation. Hence, the network traffic volumes and motor vehicle emissions for the 2030 scenarios are assumed to be the same in the analyses conducted for this dissertation. Thus, while the Test Case 2030 scenario is useful for demonstrating the capabilities of the methodologies applied in this study, the analysis results for Test Case 2030 scenario should be considered as an interim test scenario rather than an actual projected scenario.

This study thus presents a feasible methodology for evaluating the relative sustainability of different transportation and land use scenarios. It is to introduce the multiple criteria decision making (MCDM) approach and demonstrate an application for incorporating a more comprehensive concept of sustainable transportation in decision making in order to identify a superior plan for predetermined sustainability-oriented objectives. The multiple criteria decision making (MCDM) method enables the aggregation of individual performance measures into four basic indexes and further into a composite sustainability index based on regional goals and priorities. The value of the indexes lies in their ability to capture the multidimensional nature of sustainability as well as important tradeoffs among the conflicting decision criteria. A decision support tool is proposed to visualize dominance and tradeoffs when evaluating alternatives and to effectively reflect changing regional priorities over time. The proposed framework should help decision makers with incorporating sustainability considerations into transportation planning as well as identifying superior plans for predetermined objectives.

1.5. Research Contribution

This research contributes in a number of ways to essentially incorporating sustainability considerations into transportation planning. First, the study presents the state-of-the-art and the state-of-the-practice of addressing transportation system sustainability in reference to incorporating sustainability considerations in transportation planning and decision making. Second, the study proposes an integrated framework for evaluating sustainability outcomes resulting from competing transportation and land use plans by incorporating relevant spatial and environmental analyses. Third, the proposed decision support tool and the sustainability index system enable decision makers to consider the multidimensional nature of sustainability as well as dominance and tradeoffs among the conflicting decision criteria. These tools are particularly versatile in capturing uncertainties commonly inherent in the decision making process by reflecting changing regional priorities and subjective preferences over time and space.

Integrating sustainability considerations into the planning process will force decision makers to view different transportation plans in a much broader context, particularly with respect to evaluating the tradeoffs associated with implementing alternative transportation plans and possibly land use scenarios. It will also encourage decision makers to consider the idea of sustainable development priorities, recognizing that as transportation needs, land development patterns, and the quality of the environment and economy evolve, different sustainability dimensions may emerge as the transportation development priorities for a region.

1.6. Dissertation Outline

Following the introductory chapter, Chapter 2 reviews existing research efforts on definitions, performance measures, and evaluation methodologies of transportation system sustainability. Chapter 3 presents four case studies on transportation system sustainability issues in different countries with relatively different socioeconomic conditions and political/administrative institutions. Chapter 4 contemplates what constitutes transportation system sustainability and the interactions among these elements affecting sustainability. Chapter 5 discusses the research methodology as well as selected data for sustainability evaluation and the regional context of the Metropolitan Atlanta

Area. Chapter 6 evaluates competing transportation and land use plans based on a broad range of sustainability parameters using relevant spatial and environmental analyses. A decision support tool combined with a sustainability index system is also proposed in the chapter. Chapter 7 presents an extensive sensitivity analysis on different weighting schemes to enable decision makers take into consideration the subjective preferences inherent in the decision making process. Chapter 8 summarizes the findings and implications of the dissertation and concludes with directions for future research.

CHAPTER 2

LITERATURE REVIEW

The main objectives of the literature review are to characterize the current thinking on what constitutes transportation system sustainability and how it is measured. The first section discusses the state of the practice on definitions and performance measures of sustainability by reviewing national or international initiatives on sustainability measurement using indicator systems. The second section identifies a number of emergent methodologies being used to evaluate sustainability in transportation systems planning and provision. The third section then explores the multiple criteria decision making methodology which effectively captures the multidimensional nature of sustainability. This section reviews the definitions and categories of the multiple criteria decision making methodology and identifies relevant applications of this method in transportation planning and policy making.

2.1. Definitions and Performance Measures of Sustainable Transportation

The first section of the Literature Review chapter is largely from Jeon and Amekudzi (2005), which conducted comparative analysis of sixteen sustainability initiatives around the world. The review assesses initiatives on sustainable transportation systems including several national or international level studies undertaken by different organizations. The initiatives include two national studies in United States (U.S.), seven national studies in Canada, two worldwide-level studies, three European studies with an international focus, and other studies conducted in the United Kingdom and New Zealand. A majority of the initiatives are taking place in Europe and Canada. The common goals of these initiatives are to develop appropriate indicators for measuring sustainability in terms of particular needs identified and captured in various definitions of sustainability.

2.1.1. Definitions of Sustainable Transportation

Sustainable development is most commonly defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). While there is no standard definition for a sustainable transportation system, there is emerging consensus that such a system should be effective and efficient in providing its users with equitable and safe access to basic social and economic services, should promote economic development, and not be harmful to the environment (Jeon and Amekudzi 2005). Major organizations such as the Organization for Cooperation and Economic Development (OECD) and the Center for Sustainable Transportation (CST) of Canada have adopted definitions for sustainable transportation. Table 2 shows several working definitions of sustainable transportation and sustainability approved by Ontario Roundtable on Environment and Economy (ORTEE), the OECD, the Transportation Association of Canada (TAC), California DOT (Caltrans), the CST, Victoria Transport Policy Institute (VTPI), Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems (PROSPECTS), and the Department of Sustainable Development in the United Kingdom. In the United States, the mission statements of more than 40% state Departments of Transportation (DOTs) now include sustainability either explicitly or implicitly (See Table 1). In addition, a growing number of organizations around the world have begun to develop and use indicator systems to measure their progress toward transportation system sustainability (Jeon et al. 2006).

Table 2 Working Definitions of Sustainability (Transportation and General)

Organization	Definitions of Sustainable Transportation and Sustainability
Ontario Roundtable on Environment and Economy (ORTEE) 1995. Canada.	(1) Produce outputs (emissions) at a level capable of being assimilated by the environment. (2) Have a low need for inputs of non-renewable resources (where non-renewable are used, their use will be for non-consumptive investments and they will be recycled when no longer useful or needed). (3) Minimize disruption of ecological processes, land (and water area) use is also minimized as well as uses of sensitive habitats.
Organization for Economic Cooperation and Development (OECD) 1999.	Environmentally sustainable transportation is defined as: "Transportation that does not endanger public health or ecosystems and that meets needs for access consistent with (a) use of renewable resources at below their rates of regeneration, and (b) use of non-renewable resources below the rates of development of renewable substitutes."
Transportation Association of Canada (TAC) 1999. Canada.	(1) In the *natural environment*: limit emissions and waste (that pollute air, soil and water) within the urban area's ability to absorb/recycle/ cleanse; provide power to vehicles from renewable or inexhaustible energy sources (such as solar power in the long run); and recycle natural resources used in vehicles and infrastructure (such as steel, plastic, etc.). 2) In *society*: provide equity of access for people and their goods, in this generation and in all future generations; enhance human health; help support the highest quality of life compatible with available wealth; facilitate urban development at the human scale; limit noise intrusion below levels accepted by communities; and be safe for people and their property. 3) In the *economy*: be financially affordable in each generation; be designed and operated to maximize economic efficiency and minimize economic costs; and help support a strong, vibrant and diverse economy.
California Department of Transportation (2001)	A sustainable transportation system meets the basic mobility and accessibility needs of current and future generations.
The Center for Sustainable Transportation (CST) 2002. Canada.	(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 ability to absorb them, minimizes consumption of non-renewable resources, reuses and recycles its components, and minimizes the use of land and the production of noise.
Victoria Transport Policy Institute (VTPI) 2003. Canada.	Providing for a secure and satisfying material future for everyone, in a society that is equitable, caring, and attentive to basic human needs
Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems (PROSPECTS) 2003.	A sustainable urban transport and land use system: (1) provides access to goods and services in an efficient way for all inhabitants of the urban area; (2) protects the environment, cultural heritage and ecosystems for the present generation, and (3) does not endanger the opportunities of future generations to reach at least the same welfare level as those living now, including the welfare they derive from their natural environment and cultural heritage.
Department of Sustainable Development. 2003. United Kingdom.	Sustainable development is about ensuring a better quality of life for everyone, now and for generations to come. This requires meeting four key objectives at the same time in the U.K. and the world as a whole: (1) social progress which recognizes the needs of everyone; (2) effective protection of the environment; (3) prudent use of natural resources, and (4) maintenance of high and stable levels of economic growth and employment.

Updated from (Jeon and Amekudzi 2005).

While the definitions of sustainable transportation reveal that there is no standard way in which sustainable transportation is being considered, there seems to be a consensus that progress must occur on at least three fronts: economic development, environmental preservation, and social quality of life (Environment Canada, 1991 and 2003). This three-dimensional framework for sustainability seems to be the substance of operational definitions of sustainable transportation and other infrastructure systems, both in practice and research. The actual indicators and metrics selected for capturing progress in these three dimensions may however be different for different agencies (Jeon and Amekudzi 2005).

2.1.2. Frameworks for Performance Measures of Transportation Sustainability

The current state-of-the-practice in sustainability measurement is through performance indicator systems to capture relevant themes and dimensions of sustainability. Several frameworks for developing performance measures of sustainability may be found in the literature for measuring progress toward sustainability in transportation and other infrastructure systems. Similar to the existing definitions of transportation sustainability, a standard framework for constructing performance indicators that monitor progress toward sustainability does not exist. However, the literature review provides a useful basis for the development of performance measures around common themes and dimensions in such frameworks.

2.1.2.1. Indicator Frameworks

Most of the sustainability indicators in the literature have been defined using frameworks that may be categorized as: (1) linkages-based frameworks, (2) impacts-based frameworks, and (3) influence-oriented frameworks. The existing and emerging evaluation frameworks attempt to capture at least one of the following: (1) the causal relationships that lead to progress toward or deviation away from sustainability, (2) the impacts of decisions on the three common areas that define sustainability, i.e., the economy, environment, and social well-being or quality of life, and (3) the level of influence or control that the responsible agencies have over the causal factors of sustainability.

The term “linkages-based” is used to refer to frameworks that capture relationships between the causal factors, impacts, and corrective actions related to achieving sustainability. The term “impacts-based” is used to capture frameworks that focus on the nature and extent of various kinds of impacts (e.g., economic, environmental, social) that collectively determine the sustainability of a system (without necessarily capturing causal factors and corrective actions). The term “influence-oriented” is used to capture frameworks that are developed bearing in mind the relative levels of influence that the responsible agency or organization has on various actions and/or activities that influence progress toward sustainability. In a sense, these frameworks can be viewed as being more sensitive to the existing institutional constraints for addressing transportation sustainability. The section below describes selected frameworks from the sixteen initiatives (Table 3) as well as other examples from the research literature. Each of these frameworks can be placed into one of the three categories described above. In developing definitions and indicator systems, communities and agencies may also choose to adopt a process-based approach, heavily involving community representatives and other stakeholders in defining a vision for sustainability and adopting policies to achieve this vision (Jeon and Amekudzi 2005).

Table 3 Overview of Sixteen Sustainable Transportation Initiatives

Source	Funding	Overview
United States Department of Transportation (USDOT) 2003. Performance Report 2004 Performance Plan, Washington D.C. (http://www.dot.gov/PerfPlan2004/index.html)	USDOT	DOT has defined five strategic goal areas covering *safety*; *mobility*; *economic growth and trade*; *human and natural environment*; and *national security*. For each goal a set of strategic outcome goals and a number of more specific performance measures are defined for use in the annual performance planning.
United States Environmental Protection Agency (USEPA) 1999. Indicators of the Environmental Impacts of Transportation. Updated Second Edition. Washington D.C. (http://www.epa.gov/otaq/transp/99indict.pdf)	USEPA	The reports attempt to provide a comprehensive overview of the full range of environmental impacts (including impacts on air, water, climate, natural habitats, and other endpoints) from transportation modes (including road, rail, air, sea), in a system-wide perspective (including impacts from production, use and scrapping of vehicles and infrastructure).
Transport Canada (TC) 2001. Sustainable Development Strategy 2001-2003. Ottawa. Canada.	Moving on Sustainable Transportation (MOST) Program, Minister of Transport, Canada	The reports are structured around a set of seven *challenges*, broken down into 29 *commitments*, again broken down into targets and performance indicators. Three levels of indicators, reflecting different spheres of influence, include *state level indicators* (describing the state of the transportation systems in terms of sustainability), *behavioral indicators* (describing the behavior or activities of the actors and stakeholders whose actions matter for the state of the system), and *operational indicators* (describing indicators for operations and actions of Transport Canada itself).
National Round Table on the Environment and the Economy (NRTEE) 2003. Environment and Sustainable Development Indicators for Canada. Ottawa. Canada. (http://www.nrtee-trnee.ca/eng/programs/Current_Programs/SDIndicators/ESDI-Report/ESDI-Report-E.pdf)	Environment and Sustainable Development Indicators (ESDI) Initiative, Minister of Finance, Canada	The NRTEE has developed a draft set of sustainable transportation principles that concern access, equity, individual and community responsibility, health and safety, education and public participation, integrated planning, land and resource use, pollution prevention, and economic well-being.
Ontario Roundtable on Environment and Economy (ORTEE) 1995. Sustainability Indicators: The Transportation Sector. Toronto. Canada.	N/A	The report develops and assesses indicators for evaluating the impacts of possible actions or measures on the sustainability of the transportation system in Ontario. The framework adopted is based on a *'Criterion-Influences-Actions-Measures'* system. The conceptual model adopted is a computerized revised version of the 'environment-economy linkages model'.
Transportation Association of Canada (TAC) 1999, Ottawa. Canada. (http://www.tac-atc.ca/english/productsandservices/ui/exec.asp)	N/A	TAC presents 13 principles pointing to sustainable transportation systems and related urban land use in Canada in 1993. A survey to monitor trends towards attainment of the principles can be considered as framing indicators or potential indicators to the extent that they provide appropriate quantitative responses.

Table 3 continued

Source	Funding	Overview
The Center for Sustainable Transportation (CST) 2002. Sustainable Transportation Performance Indicators (STPI), Toronto, Canada.	Centre for Sustainable Transportation and the Government of Canada (Environment Canada and Transport Canada)	The Center for Sustainable Transportation, Canada developed initial set of 14 sustainable transportation performance indicators (STPI). They adopted four criteria to select the indicators: the indicators must be relevant to the definition, a time series, represent all of Canada, and come from a reliable source. The direction of the graph representing time series numbers for each indicator shows whether progress has been made towards sustainable transportation or not.
Organization for Economic Co-operation and Development (OECD) 1999b. Indicators for the Integration of Environmental Concerns into Transport Policies, Environment Directorate, Paris, France.	N/A	The document pertains to the integration of environmental concerns into transport policies through the development and use of indicators. The indicators are structured according to three themes: sectoral trends of environmental significance; environmental impacts of the transport sector; and economic linkages between transport and the environment.
Segnestam, Lisa 1999. Environmental Performance Indicators (second edition), World Bank, Environmental Economics Series, Paper No. 71 (http://wwwds.worldbank.org/servlet/WDSServlet?pcont=details&eid=000094946_0001250540075)	World Bank Environment Department	The Bank's Environmental Economic and Indicators Unit (EEI) has prepared a manual on environmental performance indicators (EPIs). This document discusses indicator frameworks, selection criteria for environmental project indicators, and issues to consider for various environmental areas.
Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems (PROSPECTS) 2003. Developing Sustainable Urban Land Use and Transport Strategies: Methodological Guidebook: Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems	European Commission's Energy, Environment and Sustainable Development Programme	The purpose of the report is: (1) To present a coherent but flexible general approach to planning for a sustainable urban land use/transport system, building on the logical structure; (2) To offer innovative methods of carrying out the steps of that logical structure, especially regarding appraisal of land use/transport strategies with respect to sustainability, and optimization with respect to sustainability, and (3) To provide detailed advice on a number of issues in the planning process.
European Environment Agency (EEA) 2002. Transport and Environment Reporting Mechanism (TERM) 2002 - Paving the way for EU enlargement: Indicators of transport and environment integration, Environmental Issues, Copenhagen, Denmark.	European Environment Agency (EEA), European Union (EU)	The report describes the progress the EU is making towards the integration of environmental concerns into its transport policies. The aim is to monitor progress in three areas: the degree of environmental integration in the EU transport sector, progress towards transport systems that are more compatible with sustainable development, and the effectiveness of the adopted policy measures.

Table 3 continued

Source	Funding	Overview
Baltic 21 Series No 13/98: Indicators on Sustainable Development in the Baltic Sea Region (An initial Set): Baltic 21 Transport Sector Report (no8/98). Annex 5: Indicators for Sustainable Transportation, Stockholm, Sweden (http://www.ee/baltic21)	Ministry of Environment	Baltic 21 selects indicators according to three different types of goals and measures: (1) Indicators with regard to primary goals for sustainable transport, (2) Indicators with regard to institutions, instruments, and measures, (3) Indicators with regard to the transport system and transportation activity
Department of Sustainable Development. 2003. Achieving a better quality of life, Review of progress towards sustainable development, United Kingdom, (http://www.sustainable-development.gov.uk/ar2002/pdf/ar2002.pdf)	Department for Environment, Food & Rural Affairs	The U.K. presents the ten guiding principles: (1) Putting people at the centre, (2) Taking a long term perspective, (3) Taking account of costs and benefits, (4) Creating an open and supportive economic system, (5) Combating poverty and social exclusion, (6) Respecting environmental limits, (7) The precautionary principle, (8) Using scientific knowledge, (9) Transparency, information, participation and access to justice, and (10) Making the polluter pay.
New Zealand Ministry of the Environment 1999, Proposals for Indicators of the Environmental Effects of Transport (http://www.mfe.govt.nz/publications/ser/transport-proposals-full-jun99.pdf)	New Zealand Ministry for the Environment	The main purpose of the document is to provide the basis for agreement on the use of a core set of indicators to measure the environmental effects of transport. The components of the framework are these: (1) root causes of transport activity, (2) indirect pressures, (3) direct pressures, and (4) state or effects indicators

2.1.2.1.1. Linkages-Based Frameworks

Linkages-based frameworks for indicators and metrics capture the full range of indicators and metrics that *cause* particular conditions affecting sustainability, the *impacts* of these causes and *corrective actions* that can be taken to address them. A widely used example of a linkages-based framework is the *Pressure-State-Response* (PSR) framework. Developed in Canada (Gilbert and Tanguay, 2000), the framework was initially proposed by Tony Friend and David Rapport for the purpose of analyzing interactions between environmental pressures, the state of the environment, and environmental responses. The PSR framework is based on the concept of causality. It states that human activities exert *pressures* (such as pollution emissions or land use changes) on the environment, which can induce changes in the *state* of the quality and quantity of the environment (such as changes in ambient pollutant levels, habitat diversity, water flows, etc.). Society then *responds* to changes in pressures or state with environmental and economic policies and programs intended to prevent, reduce, or mitigate pressures and/or environmental damage (OECD, 1999a). Figure 2 shows the framework of the PSR model. The model depicts that human activities exert pressures on the environment and affect the quality/quantity of life and natural resources ("state"); society responds to these changes through environmental, economic, general and sectoral policies and through changes in awareness and behavior ("societal response"). The PSR model has the advantage of highlighting these linkages, and helping decision-makers and the public to see environmental and other issues as interconnected (OECD, 1999a).

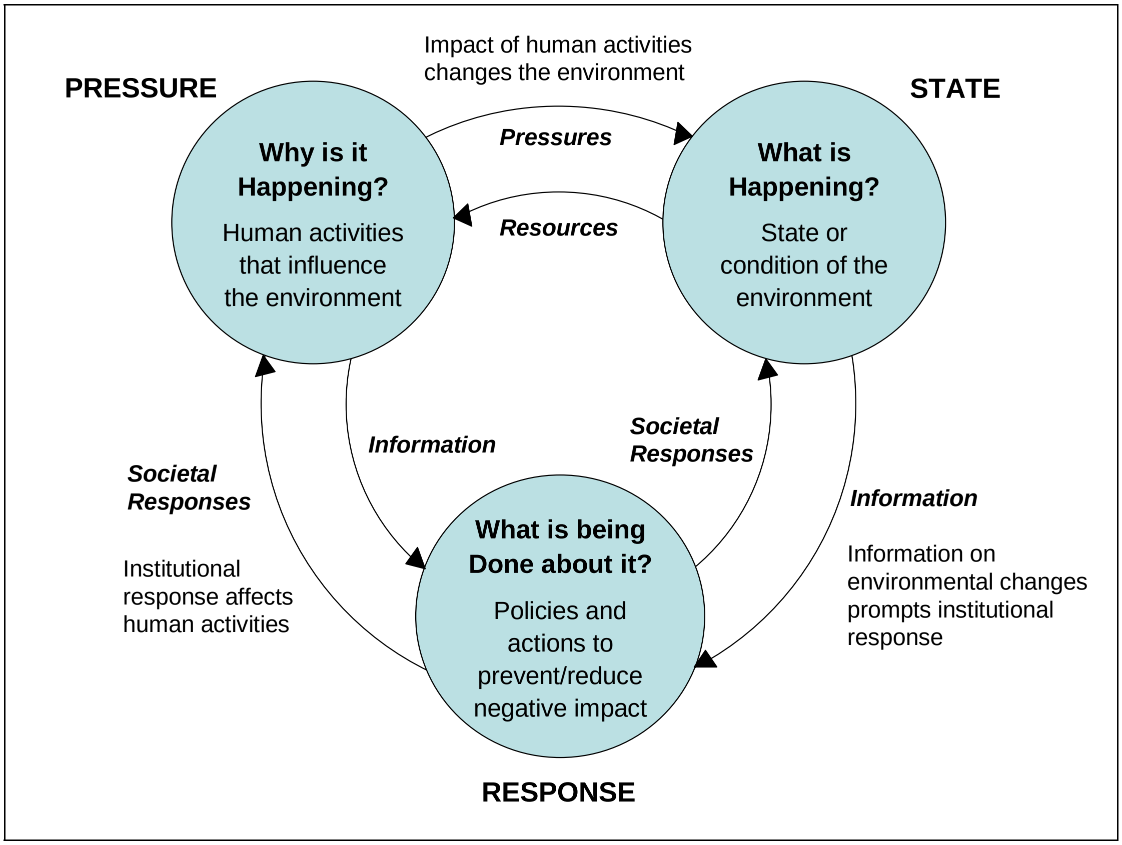


Figure 2 Pressure-State-Response Model (OECD, 1999a)

Based on its wide usage, the PSR framework can be identified as a commonly agreed upon framework for indicators. Since the 1970s, the Organization for Economic Cooperation and Development (OECD) has applied an adapted version of the framework to its work on environmental reporting. The relevance and usefulness of the PSR model was reevaluated in 1989/90 when the OECD initiated its work on environmental indicators. In developing a core set of environmental indicators, OECD countries agreed that the PSR model was a robust and useful framework and should continue to be used in the Organization's work on environmental data and indicators (OECD, 1999a).

The OECD's indicator development is thus based on a modified version of the PSR model, adapted to take into account specificities in the transportation sector. The model has been modified to distinguish between two categories of pressures: *driving forces* and *pressures*, and two categories of state: *state* and *impact*. The modified model is called DPSIR (Drivers-Pressures-State-Impact-Responses). The DPSIR model has been adopted as the most appropriate way to structure environmental information by most member states of the European Union (EU) and by international organizations dealing with environmental information, including the European Environmental Agency and EUROSTAT, the statistical office for the European Communities (Gilbert and Tanguay, 2000).

Another example of the linkages framework is seen in the work of the Ontario Round Table on Environment and Economy (ORTEE). ORTEE has adopted a framework based on a Criterion–Influences–Actions–Measures (CIAM) system. The conceptual model adopted was a computerized revised version of the "environment–economy linkages model" developed by Hickling Corporation and Econometrics Research Limited in 1993. The CIAM system, similar to the PSR framework, is really a model of the relationships among sustainability criteria, the output being the set of indicators. The model connects environmental discharge and resource use, on a country-basis, to a regionalized input-output model of the Ontario economy. A selected criterion, such as carbon dioxide emissions, for example, can be deconstructed into a number of influences (e.g., persons per vehicle, vehicle kilometers traveled etc.). These influences can trigger different actions by policy makers such as the establishment of new transit lines or car pool databases. These actions can, in turn, be facilitated by different policy measures (Gilbert and Tanguay, 2000).

Indicator systems developed based on this framework can help agencies to develop a better understanding of the actions and activities that are influencing the state of the system, and appropriate responses for addressing them, both for the agency and other stakeholders of the system.

2.1.2.1.2. Impacts-Based Frameworks

Impacts-based frameworks are focused on the *impacts* of various actions on the sustainability of the particular system under consideration. A common impacts-based framework is the three-dimensional framework of indicators based on economic, environmental, and social impacts. The tripartite framework, as it is known in some of the research literature (see for example Ashley and Hopkinson, 2002) has also been used in evaluating transportation system sustainability. For example, the evaluation framework proposed for sustainable urban transportation systems by the Transportation Association of Canada (TAC) has three dimensions related to the economy, natural environment, and society. In the natural environment, the system is expected to limit emissions and waste; in society, it is expected to provide equity of access for people and their goods, enhance human health and support the highest quality of life compatible with available wealth; and, in the economy, it is expected to help support a strong, vibrant, and diverse economy (TAC, 1999). The Victoria Transport Policy Institute (VTPI) uses a similar framework for sustainable transportation indicators. Although VTPI has a stronger focus on transportation and land use interactions, their comprehensive list of sustainable transportation indicators are also organized according to economic, social, and environmental impacts (Litman, 2003).

The tripartite framework is also found in the research literature for addressing sustainability in other types of civil infrastructure systems. Ashley and Hopkinson (2002), for example, present a tripartite framework as key groups of indicators to characterize alternative measures of sustainable development in decision making for water and sewer systems. For each of the three dimensions: *economic*, *ecological,* and *socio-political*, important aspects are identified and then measurement methods and measures are developed for each aspect. For example, growth, equity, and efficiency are identified as important aspects of economic sustainability; and methods such as the Green Gross National Product and resource accounting are identified for measuring progress in these domains, using such relevant measures as money and energy per unit of expenditure. Balkema et al. (2001) also present a tripartite framework for measuring sustainable technology in waste water treatment systems based on the nature and extent of the interaction of technology with the *economic*, *physical,* and *socio-cultural* environment.

Using a similar paradigm, Pearce and Vanegas (2002) discuss the thermodynamic foundations of sustainability and develop three parameters for measuring technological sustainability in decision making for building infrastructure. The thermodynamic foundations of sustainability assume that the earth is a constrained open system (virtually closed) with solar radiation as an input and waste heat as an output. While there is no net loss of matter or energy, there is degradation of energy from higher to lower forms, i.e., entropy. Entropy results from consumption and is offset by natural ecosystems in the form of photosynthesis (Pearce, 2000). Thus, from a thermodynamic standpoint, the two objectives necessary to maintain sustainability of the global earth system are: (I) to minimize the consumption of matter and energy; and, (II) to minimize negative impacts to natural ecosystems, as they are the only mechanism for offsetting the entropy resulting from consumption. These concepts of consumption and environmental impact minimization can extended to the operation and management of built systems, where the objectives become exploring investment options that achieve comparable levels of system performance with a net reduction in system inputs, e.g., the total energy consumed per mile of travel in a metropolitan transportation system, and outputs, e.g., total amount of pollutants emitted by the system in a specified period. Pearce and Vanegas (2002) extend this concept to develop the following three dimensions for measuring technological sustainability: (I) the *level of stakeholder satisfaction*, (II) the *resource base impact*, and (III) the *ecosystem impact*. Figure 3 shows the triaxial representation of the parameters for technological sustainability. The figure illustrates that in selecting among alternatives to move building (and other infrastructure) systems toward sustainability, the alternatives should satisfy stakeholders (i.e., they should not necessarily be *optimal* but *satisficing* with regard to stakeholder desires), while having a net positive or neutral impact on the resource base and the natural environment (i.e., they results of decisions should lie in the "octant of sustainability").

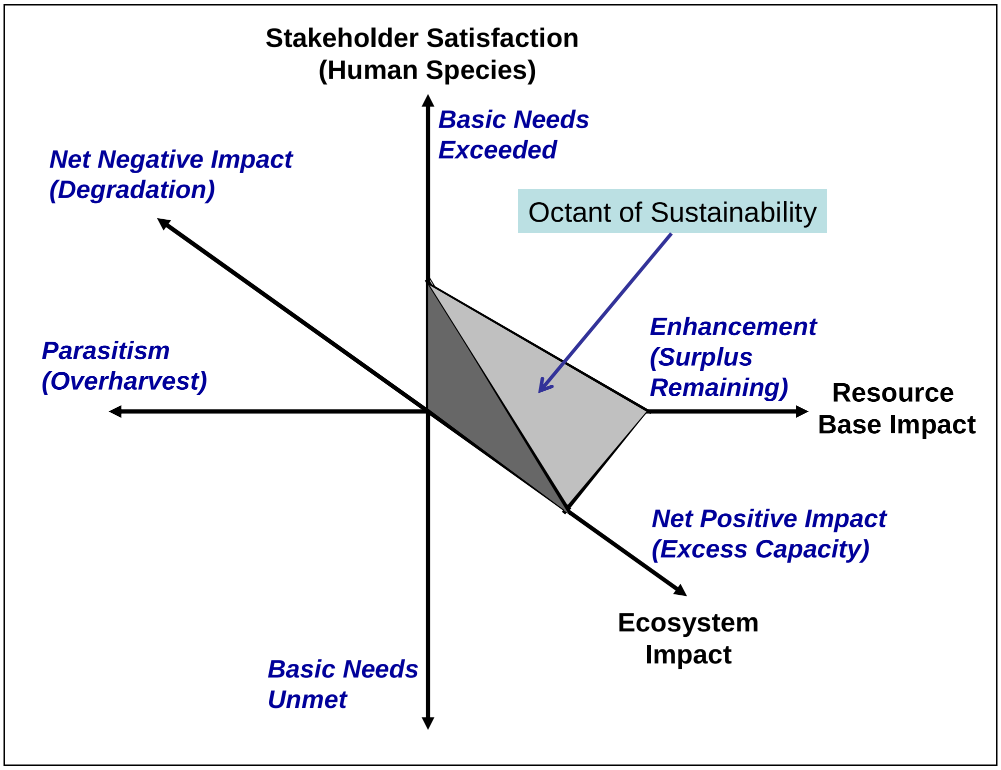
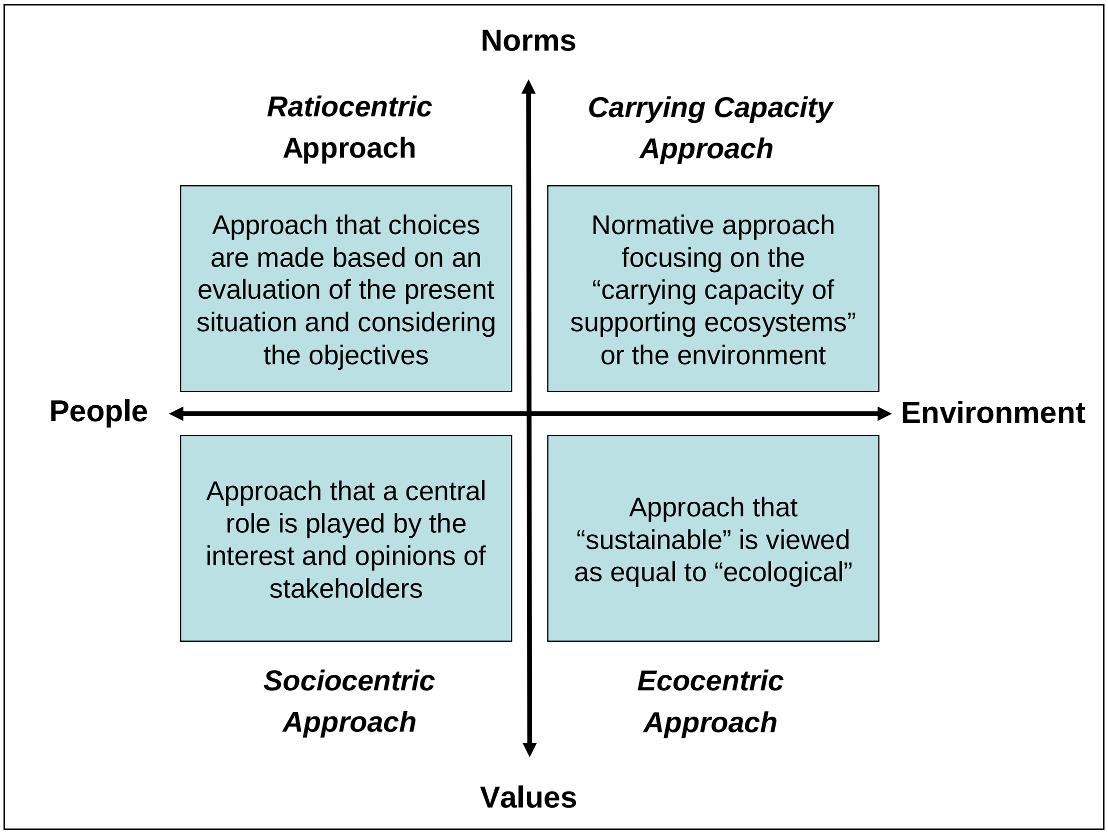


Figure 3 Triaxial Representation of Technological Sustainability (Pearce and Vanegas, 2002)

Also using a similar paradigm, Rijsberman and van de Ven (2000) discuss four basic approaches to sustainability, which are influenced by four aspects: *people*, *norms*, *values*, and the *environment*. In this framework, two contrasting attitudes toward the relationship of people-environment can be distinguished. In a people-driven approach, people and their desires, needs, and objectives are the driving forces behind the perception of sustainable development. Environment-driven approaches, on the other hand, state that the seriousness and extent of environmental problems should be established objectively from nature. The way in which this relationship or interaction is evaluated can also be distinguished by two contrasting approaches: a quantitative approach based on norms, and a qualitative approach based on values. Various combinations of these four aspects result in four basic approaches: (I) norms and environment: *capacity* approach; (II) norms and people: *ratiocentric* approach; (III) values and people: *sociocentric* approach and (IV) values and environment: *ecocentric* approach (See Figure 4).



Approach that choices are made based on an evaluation of the present situation and considering the objectives

Normative approach focusing on the “carrying capacity of supporting ecosystems” or the environment

Approach that a central role is played by the interest and opinions of stakeholders

Approach that “sustainable” is viewed as equal to “ecological”

Figure 4 Normative, Ecocentric, Ratiocentric, and Sociocentric Approaches to Sustainability (Rijsberman and van de Ven, 2000)

The carrying capacity approach is a normative approach that focuses on the carrying capacity of supporting ecosystems or the environment and develops target values that are sustainable levels of environmental stress within the existing carrying capacities of various norms, e.g., air quality, water quality etc. The ecocentric approach views sustainability as ecologically feasible. The objectives are not met by trying to meet stringent norms but by creating positive conditions for desired development. It is more of a proactive than reactive approach. In the ratiocentric approach, choices are made based on the evaluation of multiple criteria in the present situation, considering the objectives of decision making, and evaluating all interests involved. In a sociocentric approach, the interests and opinions of stakeholders are central, and priorities are set in an interactive process. This is a qualitative approach that emphasizes participation in the objectives of decision making and the decision making itself. These four approaches point out various emphases that can be made in sustainability planning, depending on the existing decision-making context, institutional constraints, data availability, relative levels of stakeholder interest and involvement, presence or absence of executives and/or political leaders who are champions of sustainability, and other relevant resources.

2.1.2.1.3. Influence-Oriented Frameworks

Influence-oriented frameworks categorize indicators by the level of influence and control that the responsible agency has with respect to the various factors that cause or otherwise influence the sustainability of the infrastructure system under consideration. Transport Canada (2001) has developed an important tiered framework of performance indicators that reflects the relative level of influence and control that the agency has with respect to making progress toward sustainability. The framework has three levels of indicators: state level indicators, behavioral indicators, and operational indicators. *State level indicators* or state-of-the-system indicators describe the state of the transportation system in terms of sustainability. This level of indicators addresses the overall vision or goal of activities for obtaining a sustainable transportation system and measures how well the system is performing relative to this vision. *Behavioral indicator*s, on the other hand, are related to the behavior or activities of the actors and stakeholders whose actions influence the state of the system. Stakeholders include transportation infrastructure and service providers, system operators, political and other decision-makers, and the general public.

This level of indicators is relates to the mission of Transport Canada and captures the extent to which the agency's activities are resulting in behavioral and activity change within the system, which then impacts the overall goals for the system. *Operational indicators* are described as indicators for operations and actions of Transport Canada itself. This level of indicators is related to the agency's mandate, i.e., where it has clear responsibilities. As such, Transport Canada's indicator system recognizes explicitly that the agency has varied degrees of control and influence over different activities and things that influence transportation system sustainability. The indicator system explicitly recognizes that the agency has only indirect influence over the state level indicators, direct influence over the behavioral indicators, and direct control over the operational indicators (Gudmundsson, 2000).

2.1.2.1.4. Process-Based or Stakeholder Frameworks

A process-based framework of sustainability acknowledges that addressing sustainability must be approached through a planning process which effectively engages stakeholders in creating their sustainable vision. Process-based frameworks are based on a decision-making process for developing consensus, involving all the representatives from various constituencies within the community (Environmental Defense, 1999). Initiatives such as the U.S. Department of Energy's (DOE) "Ten Steps to Sustainability" outline a process for engaging communities/stakeholders in thinking about and articulating their vision for sustainability, developing a roadmap for reaching this vision, developing indicators to measure progress toward this vision, and incorporating sustainability into local policy to promote attainment of sustainability (USDOE). Process-based mechanisms are crucial for articulating the right vision for a community (at the local, state, national, or multinational levels). They are also potentially effective mechanisms for educating stakeholders and the general public about sustainability and promoting progress toward consensual sustainability goals through collective behavioral change. From an agency viewpoint, this implies that there is tremendous value in viewing public involvement as a critical component of sustainability planning.

2.1.2.1.5. Balance in Frameworks

It is important that agencies give thought to defining an appropriate balance of input (causative) versus outcome (impact) measures. Gudmundsson's evaluation of transportation sustainability initiatives in Europe and North America revealed seemingly different foci with respect to achieving transportation sustainability in Europe and North America (Gudmundsson 2000). Table 4 summarizes the foci of the different initiatives. The European Union (EU) had set up seven policy questions, Transport Canada (TC) had established seven challenges, and the United States Department of Transportation (USDOT) had established four strategic outcome goals. Gudmundsson found Europe's approach to cover a wider range of surrounding policy issues (that would affect or influence progress toward transportation sustainability), while TC and the USDOT approaches more or less concentrated on management challenges and internal responsibilities. He concluded that the North American approach seems to be reaching "outwards" for more results or outcome-oriented performance goals, while the European approach seemed to be reaching "inwards" for policy-related response or input. An appropriate balance of input and outcome measures, distributed appropriately across the various responsible agencies in a manner that is consistent with their different missions and spheres of influence, could be more effective for addressing sustainability.

Table 4 Input and Output-Oriented Systems for Achieving Sustainable Transportation

EU 2000 **Transport and Environment Reporting Mechanism** **"7 Policy Questions"**	**Transport Canada 2000** **Sustainable Development Strategy** **"7 Challenges"**	**US DOT 1997** **Strategic Goals - Human and Natural Environment** **"4 Strategic Outcome Goals for the Environment"**
Is the environmental performance of the transport sector improving?	Reducing Pollution of Land and Water Reducing Air Emissions	Reduce the amount of transportation-related gases released Reduce the adverse effects of siting, construction and operation of transportation facilities
Are we getting better at managing transport demand and at improving the modal split?		
Are spatial and transport planning becoming better coordinated so as to the needs of access?		Improve the sustainability and livability of communities through investments in transportation facilities
Are we optimizing the use of existing transport infrastructure capacity and moving towards a better-balanced intermodal transport system?	Promoting a More Efficient Transportation System	
Are we moving towards a fairer and more efficient pricing system, which ensures that external costs are recovered?		
How rapidly are improved technologies being implemented and how efficiently are vehicles being used?	Promoting Improved Technology for Sustainable Transportation	
How effectively are environmental management and monitoring tools being used to support policy and decision-making?	Improving Environmental Management in the Transportation Sector Developing Tools for Better Decisions Improving Education and Awareness of Sustainable Transportation	Improve the natural environment and communities affected by DOT-owned facilities and equipment

Adapted from Gudmundsson (2000)

2.1.2.1.6. Synthesis of Indicator Frameworks

The indicator frameworks discussed above can be helpful in various ways to agencies that are contemplating including sustainability in their mission statements, revisions to their mission statements, or the development of indicators and metrics to evaluate progress toward predefined goals. Such frameworks have been used by various agencies to develop indicator and metric systems for addressing sustainability. For example, the initial plan of Canada's Center for Sustainable Transportation (CST) was to develop indicators that added quantitative flesh to its definition of sustainable transportation. This was achieved by deconstructing the definition of sustainable transportation into numerous elements, quantifying each element as a target, and fashioning for each target one or more indicators that represent movement toward or away from the target. CST developed three levels of sustainable transportation performance indicators (STPI), a single composite indicator with descriptive indicators that reflect the components of the single indicator, and explanatory indicators that enhance understanding of transportation activities and their impacts. Descriptive indicators (similar to state indicators in the PSR framework) were developed to represent the effects of transportation and whether these effects were changing in directions consistent with sustainability. Explanatory indicators (similar to pressure indicators in the PSR framework) were developed to represent contributory factors that can help explain changes in descriptive indicators and that contribute to policy formulation (CST, 2002).

Agencies can also combine the frameworks to help them develop more comprehensive indicator systems. For example, an indicator system that includes all the three elements: i.e., one that is linkages-based, impacts-based, and influence-oriented, would help an agency to understand the most effective actions they can take (linkages element) to make progress in selected domains (impacts element, e.g., safety, economics, environment etc.,) related to their mission (level of influence element). Such a comprehensive framework could also be useful for thinking about an appropriate balance of input (or inward-looking) indicators versus output (or outward-looking) indicators (as captured in Table 4). Figure 5 illustrates this concept of a unified framework for developing indicator and metric systems. The unified framework identifies three attributes for guiding the development of indicator systems: (I) what level of influence does the agency have over this indicator (x-axis)? (II) Is the indicator an input or output of the system (y-axis)? (III) And what is the relative level of impact of this indicator on achieving system sustainability (z-axis)?

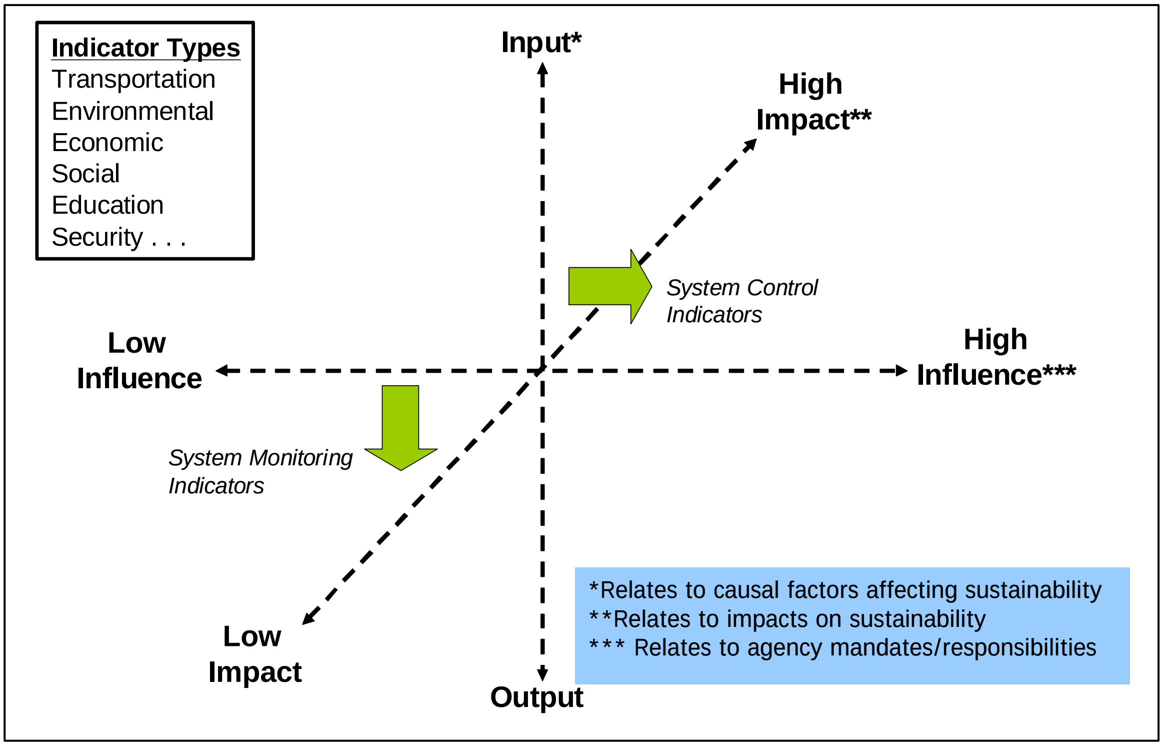


Figure 5 Unified Framework for Developing Indicators for Infrastructure System Sustainability

In this unified paradigm, an agency, such as one of the DOTs with a mission to develop a sustainable transportation system (see Table 1), could focus on identifying the current and predicted areas of highest impact relative to creating a sustainable transportation system, identify causal factors (inputs, y+ axis) that have the most significant effect on these high impact areas (z+ axis), narrow down on the causal factors that are within its domain of highest influence or control (related to its mission) (x+ axis), and then begin to develop policies, planning procedures, databases, and analysis tools to address these areas. Such an approach could also be used in defining transportation system sustainability in a manner that is most relevant to an agency and its jurisdiction's present and future needs. Using these frameworks, in the context of a process/stakeholder-based approach, could substantively improve effectiveness and efficiency in addressing sustainability in infrastructure systems, as progress is simultaneously being made with the institutional reform, data and analytical capabilities, and education initiatives necessary to address sustainability in the longer term.

2.1.2.2. Other Indicator Frameworks

Hart (1998) also identifies four frameworks for organizing sustainability indicators: (1) category or issue lists, (2) a goal-indicator matrix, (3) driving force-state-response tables, and (4) endowment-liability-current result-process tables. Category or issue lists usually refer to organizing indicators based on the main focus of each indicator: the environmental, economic, and social aspects of the community. The goal-indicator matrix relates indicators to a range of sustainability issues or a set of community goals. Diving force-state-response tables balance measures of causes or driving forces; measures of the results, or state; and measures of programs and other human activities designed to alter driving forces with the goal of improving the state. This framework shares same essentials with the linkages-based framework identified in the prior review. The last framework uses endowments, liabilities, current results, processes as headings in a table which checks for balance among measures of what we are leaving for future, what we have now, and what is happening to create both situations (Hart, 1998). What is common to each framework is the creation of indicators around specific themes.

Zegras (2006) presents the Sustainability Indicator Prism that innovatively represents the hierarchy of goals, indexes, indicators, and raw data as well as the structure of multidimensional performance measures (Zegras, 2006). As shown in Figure 6, the top of the pyramid represents the community goals and vision, the second layer represents a number of composite indexes around the selected themes, third layer represents indicators or performance measures building from raw data at the bottom of the pyramid.

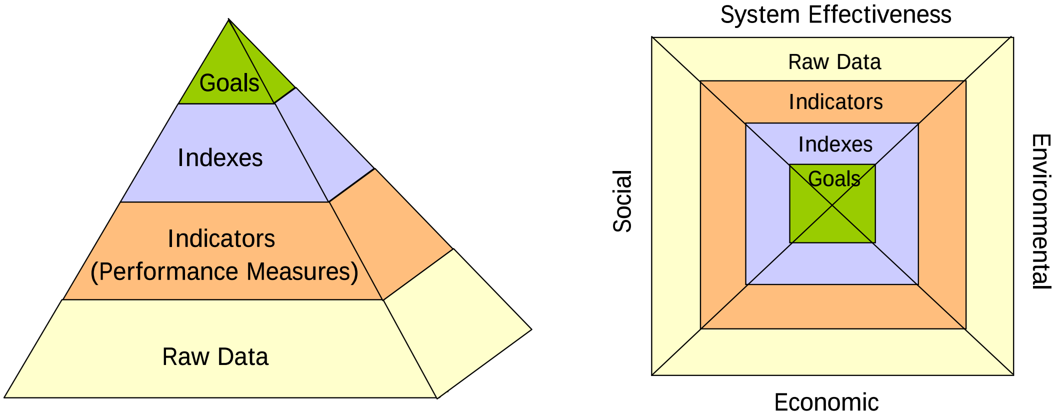


Figure 6 Sustainability Indicator Prism [Adapted from Zegras, 2006; Meyer and Miller, 2001].

This concept can also be considered as the combination of Hart's category or issue lists (environmental, economic, and social aspects) and goal-indicator matrix, which organizes indicators/indexes around a set of community goals or various sustainability issues. This framework is especially penetrating when decision makers first set the community goals for sustainability around the essential dimensions of sustainability (environmental, economic, and social dimensions, etc) and indicators and composite indexes are constructed based on the categorized goals and objectives.

2.1.2.3. Synthesis - Sustainability Indicator Frameworks

The three constructs discussed above provide a useful basis for the development of performance measures to assess the extent to which proposed plans contribute to regional sustainability. The critical points that emerge from these constructs are that performance measures must be developed to capture a community's broader vision which can be further broken down into goals and objectives. In essence, using these constructs, it becomes clear that performance measures or indicators for different regions (or other communities) may be different if their visions are different. There is thus no such thing as the correct performance measure in sustainability as much as there is/are the most appropriate measure(s) for capturing a particular vision. However, given the present status of any particular community, there may be superior and inferior visions that can be adopted relative to moving rapidly toward sustainability. These key ideas are used in the development of the performance measures in the following sections, and can serve as general guiding principles in the development of performance measures for sustainability assessment (or other planning functions) (Jeon et al., 2008).

2.1.3. Performance Measures of Sustainability

2.1.3.1. Measures reviewed by Jeon and Amekudzi (2005)

The review conducted by Jeon and Amekudzi (2005) also provided an extensive list of indicators sorted by the relative frequencies with which they appeared in the sixteen initiatives. All the transportation sustainability indicators reviewed may be classified into the following four major categories: transportation system effectiveness-related, economic, environmental, and socio-cultural/equity-related indicators. The present status of addressing sustainability in transportation planning and provision seems to indicate a higher focus on the effectiveness of transportation systems as well as the resulting environmental impacts (mainly air quality impacts), and less of a focus on economic and social impacts.

All the indicators or performance measures being used in the sixteen initiatives may be classified as one of the four categories: transportation-related, economic, environmental, and socio-cultural/equity-related (including safety). Table 5 provides a comprehensive list of the indicators and metrics being used in the sixteen initiatives to evaluate progress toward sustainability. In general, the main indicators being used to address transportation sustainability can be inferred from this table. The indicators and metrics are sorted by the relative frequencies with which they appear in the indicator systems of the sixteen initiatives.

From Table 5, it is clear that transportation-related and environmental indicators seem to be the most widely used indicators for sustainable transportation. All the sixteen initiatives have environmental indicators. Environmental indicators that seem to be in higher use are linked to vehicle emissions and fuel consumption. Common environmental indictors include emissions of various air pollutants, especially green house gases such as carbon dioxide, nitrogen oxides and volatile organic compounds

(VOCs). Fuel consumption also appears to be a common environmental indicator. Economic measures, largely captured as per capita indicators, are seen in only few of the initiatives. Canada's ORTEE and TAC, the World Bank, Europe's PROSPECTS, and New Zealand are the only initiatives with any economic indicators. Socio-cultural and equity-related indicators do not seem to be in wide use either. ORTEE, VTPI, PROSPECTS, the Baltic States and New Zealand are the only initiatives with socio-cultural/equity-related indicators, and, even so, each initiative has very few indicators in this domain. Considering safety indicators as social indicators, about half of the initiatives have safety-oriented social indicators. These indicators are largely focused on outcome measures such as injury or fatality crashes.

Thus, the synthesis of indicators in Table 5 would seem to suggest that sustainable transportation is largely being captured more by transportation effectiveness and efficiency indicators and environmental indicators; and, to a lesser extent by economic and social indicators (except safety-oriented indicators). In addition, there are significant differences in the balance of input and output measures being used in the different domains, i.e., environmental versus economics. Any analysis of these indicator systems cannot be conducted outside the context of their relative adequacy for achieving the visions that they were created to support.

2.1.3.2. Other Performance Measures

Since these initiatives were reviewed, an increasing number of sustainability-related studies have been conducted around the world. Such studies on sustainable transportation range from case studies on sustainability measurement for a particular region to the development of new or comprehensive sustainability metrics at different planning levels, such as corridor-level, intra- and inter-city level, urban-level, and macro-level global indicators. Corbiere-Nicollier and Jolliet (2002) develop indicators usable at the communal level, to determine the socio-economic and environmental impacts of various alternatives using the case of three communities in Switzerland. Federici et al. (2003) measure efficiency and sustainability for passenger and commodities transportation systems of a medium size district of central Italy: Siena. Van Den Berg et al. (2005) set out to measure the transportation performance of one South African city, the Tshwane Metropolitan Municipality (TMM), against a number of world cities. Amidst various case studies, Litman (2005 and 2007) attempts to provide the most important indicators for comprehensive and sustainable transportation planning that can be applied across the board in most situations.

Several researchers propose a single combined index of sustainability using different methodologies for aggregating individual indicators. Black (2002) develops an international-level index that measures both sustainable transportation and potential mobility using the gross domestic product (GDP) and the principal component analysis (PCA). Zietsman et al. (2003) introduce a corridor-level index that incorporates travel rates, fuel consumption, local pollutant emissions, travel cost, and safety using multi-attribute utility theory. Rassafi and Vaziri (2004) derive an international-comparative index aggregated by the concordance analysis technique to evaluate transportation system sustainability of the selected countries. Yevdokimov (2004) proposes a national-level index using the Genuine Progress Indicator (GPI) and the system dynamics approach.

More recently, several studies have incorporated a newer measure of sustainability into the evaluation process, for example the “ecological footprint.” Du et al.

(2004) propose the methodology for predicting urban ecological footprints for measuring sustainable development in forms of the ecological impact. Chi and Stone (2005) present a methodology for measuring the ecological footprint of a county-level transportation network in current and future time periods. Some researchers attempt to define and evaluate sustainability with concentrating more on a particular theme of sustainability. Colvile et al. (2004), for example, assess the sustainability of urban road transportation in terms of exposure to traffic-related air pollution by modeling the movement of air, vehicles, and vehicle exhaust emissions. Kasanko et al. (2002) monitor the evolution of urban and regional land use and traffic network in terms of various land use measures derived from the airborne imagery and remote sensing technology. Such spatial indicators include urban sprawl, reuse of abandoned land, accessibility to green urban areas, and exposure to the nuisance of transportation network.

Table 5 Indicators and Metrics for Sustainable Transportation Systems (Sixteen Initiatives)

	US DOT	US EPA	Trans Canada	EC[1]	NRTEE[2]	ORTEE[3]	TAC[4]	VTPI[5]	CST[6]	OECD	World Bank	PROSPECTS[7]	EEA[8]	Baltic	UK	New Zealand
Economic																
Population density (persons/ha)						▨	▨									▨
Economic efficiency						▨						▨				
Employment						▨	▨									
Accessibility measures												▨				
Public expenditure												▨				
Growth potential												▨				
Green GDP						▨										
GDP per unit of energy use											▨					
Tax revenues						▨										
Implementation of internalization instruments													▨			
Employment-to-population ratio in Central area							▨									
Transportation-related																
Length of railways and main roads, Parking facility								▨	▨	▨				▨	▨	▨
Passenger-kilometers (by mode, purpose)				▨					▨		▨		▨		▨	▨

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[1] Environment Canada
[2] National Round Table on Environment and Economy
[3] Ontario Round Table on Environment and Economy
[4] Transportation Association of Canada
[5] Victoria Transport Policy Institute
[6] Center for Sustainable Transportation, Canada
[7] Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems
[8] European Environment Agency

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROS PECTS	EEA	Baltic	UK	New Zealand
Freight ton-kilometers (by mode, purpose)									▨		▨		▨		▨	▨
Total kilometers driven(VMT)				▨	▨		▨		▨							▨
Unit sales of cars/trucks (Auto Use per capita)					▨					▨	▨			▨		
∑ Traffic volumes of road, rail, air, sea (vehicle-kilometers)									▨		▨			▨		
Public transit and automobile use				▨			▨	▨								
Avg. home-work trip distance/time (by purpose)							▨			▨			▨			
Portion of transportation-related costs paid by public funding (Subsidy)								▨		▨			▨			
∑ Total passenger and cargo turnover by air, ship, road, rail; mode shifts											▨			▨		
Per-capita gas consumption vs. urban density					▨		▨									
Mixed land use						▨		▨								
Average portion of Household transportation expenditures								▨	▨							
Length of public transport network										▨				▨		
Extent and density of transport Infrastructure										▨	▨					
Land Area Occupied by Roadways/Transportation Infrastructure		▨											▨			
(Morning peak) Auto occupancy to/from CBD							▨						▨			
∑ Total investment in maintenance costs wrt road/rail/harbor/air infra													▨	▨		
Growth/trend of gasoline prices and share of taxes in diesel fuel and gasoline prices (%)										▨			▨			

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROS PECTS	EEA	Baltic	UK	New Zealand
Real changes in the cost of transport													▨		▨	
Annual transit ridership	▨						▨									
Vehicle fleet composition													▨			▨
Transport intensity (passenger or ton-kilometers/GDP)										▨						
Aircraft departures											▨					
Capacity of transport infrastructure networks, by mode and by type of and services infrastructure													▨			
Short journeys per person per year by mode															▨	
Commute cost						▨										
Commute time						▨										
Total amount of external costs by transport mode													▨			
Total light-duty vehicles					▨											
Motor vehicles											▨					
Two-wheel vehicles											▨					
% of low emission vehicles purchased of total annual vehicles purchased			▨													
Diesel locomotives available											▨					
Non-auto trips (% of urban trips not by automobile)						▨										
Trips with 2 or more modes						▨										
Arterial lane-km							▨									
Expressway lane-km							▨									
HOV lane-km							▨									
Morning peak period transit seat-km							▨									
24-h transit seat-km							▨									
Off-street parking spaces per employee in CBD							▨									

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROSPECTS	EEA	Baltic	UK	New Zealand
Morning peak transit mode share to/from CBD							▨									
Morning peak auto mode share to/from CBD							▨									
24-h person trips							▨									
24-h arterial auto vehicle-km per capita							▨									
Road Utilization Index (RUI) (vehicle-km/lane-km)							▨									
Total road expenditures							▨									
Total transit expenditures							▨									
Farebox revenue/operating and maintenance budget							▨									
Average amount of residents' time devoted to non-recreational travel								▨								
Quality of public transit service, integration with other modes								▨								
Public transport performance												▨				
Quality of delivery services								▨								
Quality of mobility services for residents with special mobility needs								▨								
Share of areas larger than 100 km2 not separated by motorways														▨		
Change in level of road congestion over time																▨
Usual mode of transport for journey to work																▨
Gas and diesel fuel prices at the pump					▨											
Expenditure on personal mobility per person by income group													▨			

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROS PECTS	EEA	Baltic	UK	New Zealand
Relative transit cost (Avg. transit fare to Avg. gas cost)									■							
Load factors for freight transport (LDV, HDV)													■			
% travel meeting pavement performance standards	■															
Of total annual urban-area travel, % occurs in congested conditions	■															
Environmental																
CO_2 emissions (by mode)		■	■	■		■	■			■	■		■	■		
Greenhouse gas emissions	■			■	■				■		■		■		■	
Fossil fuel consumption				■			■		■	■			■	■		
Per-capita use of transportation energy	■				■		■	■	■					■		
Emissions of air pollutants (from Transportation Vehicle and Equipment Manufacturing)	■	■						■		■			■	■		
NOX emissions (by mode)		■							■	■			■	■	■	
VOCs emissions		■							■				■	■		
Main land use/Urban land use		■				■						■				
Fossil fuel use by auto		■		■						■						
Waste/Recycling		■	■										■			
CO emissions		■							■						■	
Emission intensity									■				■			
Noise level/cost		■										■		■		
Green area									■			■				
Toxic substances in urban air: benzene/ozone		■		■										■		
Fuel efficiency of new auto				■						■						
E-index (Per capita energy consumption)				■		■					■					
Non-fossil fuel use (Alternative fuel)						■							■			

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROS PECTS	EEA	Baltic	UK	New Zealand
Wetland losses and creation	▨	▨														
Hazardous materials incidents	▨	▨														
Maritime Oil spills	▨	▨											▨			
Overall energy efficiency for passenger and freight transport				▨									▨			
CO_2 cost[9]												▨				
SO2 emissions		▨							▨							
CH4 emissions		▨									▨					
Black smoke emissions															▨	
Lead emissions		▨													▨	
Air pollution cost												▨				
Chlorofluorocarbons and stratospheric ozone depletion		▨		▨												
Urban sprawl												▨				
Fragmentation/Particles/ Volatile organic compounds		▨		▨										▨		
Vulnerable areas												▨				
Worldwide major natural disasters					▨											
Ecological footprint						▨										
Demotechnic Index						▨										
Percentage of reused or recycled parts of different types of end-of-life vehicles														▨		
Number of Motor Vehicles Scrapped Annually, Disposition of Scrap Tires		▨														
Lead Acid Batteries in Municipal Solid Waste Streams		▨														

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[9] Emissions in tones weighted by shadow cost of national CO_2 target

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROS PECTS	EEA	Baltic	UK	New Zealand
∑ Investments dedicated to environmental protection														▨		
Percentage of arterial roads and state highways with appropriate levels of storm water treatment																▨
Sediment loads in streams (pressure indicator)																▨
Change in criteria pollutant emissions compared to vehicle travel 1940-1997		▨														
No. of animal/wildlife collisions		▨														
Water Quality		▨														
Fuel Tank Lickage		▨														
% of tanks in compliance with Guidelines			▨													
Mobile Source Contribution to Hazardous Air Pollution Inventories		▨														
Toxic Chemicals Released from Ship- and Boat Building & Repairing Facilities		▨														
Average monthly ambient air concentrations in capital/town											▨					
Fisheries Protection-Compliance rate with Federal fisheries regulations	▨															
Environmental costs and liabilities as reported to Treasury Board			▨													
Number of contaminated sites undergoing remediation or risk management			▨													
Fragmentation of ecosystems and habitats		▨											▨			
Percentage of strictly protected area				▨												

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROS PECTS	EEA	Baltic	UK	New Zealand
Change in emissions of toxic substances variable				▨												
Change in sulphur dioxide emissions (Acid Rain)		▨		▨												
Per capita water use				▨												
Municipal wastewater treatment improvement				▨												
Percentage of ecozone with strictly protected forest area				▨												
Reduction in number of bare-soil days on agricultural land				▨												
Per capita non-hazardous solid waste generation				▨												
Dredging and impacts to aquatic resources		▨														
Introduction of non-native species		▨														
Impervious surfaces		▨														
Releases of deicing chemicals, cleaning fluids, and wastewater		▨														
Solid waste (Motor vehicle scrappage, motor oil, tires, etc.)		▨														
Safety-oriented																
Deaths and injuries (Safety risks: injuries or fatalities per vkt, per vehicle)						▨	▨	▨	▨	▨			▨	▨		
Accidents											▨	▨	▨			
Accident cost												▨				
Vulnerable user accident												▨				
Medical costs attributed to transportation								▨								
Number of cases of serious pollution or health effects														▨		

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROSPECTS	EEA	Baltic	UK	New Zealand
Social-cultural/ Equity-related																
Residential population exposed to outside airport noise	▨	▨											▨			▨
Accessibility for those without a car								▨				▨	▨			
Residential population exposed to outside road traffic noise		▨											▨			▨
Avg. No. of major services within walking distance of residents and Avg. walking distance between residences and public services								▨		▨				▨		
% increase in environmental awareness, as measured by surveys or testing			▨										▨			
Local activity												▨				
Quality of transit wrt mobility impaired												▨				
Income inequality												▨				
Equity impact tables												▨				
User benefit inequality												▨				
Benefits by zone												▨				
Taxpayer' money												▨				
Crime						▨										
Community disruption						▨										
Distribution Inequality Index						▨										
Vehicle access						▨										
Quality of pedestrian and bicycle environment								▨								
Affordability of public transit service by lower income residents								▨								
Proportion of residents with public transit service within 500 meters	▨															

Table 5 continued

	US DOT	US EPA	Trans Canada	EC	NRTEE	ORTEE	TAC	VTPI	CST	OECD	World Bank	PROSPECTS	EEA	Baltic	UK	New Zealand
Residents' participation in transportation and land-use decision making								▨								
Consumer perception of satisfaction with air quality		▨														
Environmental justice-Environmental justice cases that remain unresolved over one year	▨															
% of Environmental emergency plans in place (% of plans up to date)			▨													
Population exposed to exceedances of EU air quality standards for PM10, NO2, benzene, ozone, lead and CO													▨			
Proximity of transport infrastructure to designated areas													▨			
Regional access to markets: the ease of reaching economically important assets by various modes													▨			
Extent of Performing Transport/ Environment Integration Management													▨			
% of bus fleets/key rail station with ADA compliant	▨															
Access to basic service										▨						

2.1.4. Findings and Implications

The review and synthesis of the literature on sustainability in transportation and other infrastructure systems lead to a number of important findings. First of all, it is clear that sustainability in infrastructure systems planning and provision is an issue of growing importance based on ongoing activity in practice and research to define and measure sustainability in infrastructure systems. Second, while there are no standard definitions for sustainable transportation systems, there is consensus that sustainable transportation must impact at least three areas: the economy, the environment, and overall social well-being. Third, while there is no standard framework for evaluating progress toward sustainability, it is clear that the existing and emerging evaluation frameworks try to do at least one of the following: (I) capture the causal relationships that lead to progress toward or deviation away from sustainability; (II) capture the impacts of decisions on the three important areas that define sustainability: i.e., the economy, environment and social well-being or quality of life, and, (III) capture the level of influence or control that the responsible agencies have over the causal factors of sustainability. In addition, a stakeholder or process-based approach seems critical in sustainability planning for capturing the visions and values of different communities at various sociopolitical levels (local, state, national, and multinational). Fourth, the present status of addressing sustainability in transportation planning and provision seems to indicate a higher focus on the effectiveness and efficiency of transportation systems planning and provision as well as the resulting environmental impacts, and less of a focus on economic and social impacts.

Generally absent in the sixteen initiatives reviewed are considerations of education initiatives to promote awareness of the importance, benefits, and challenges of moving toward sustainability. Public education is clearly an integral component of any systematic initiative to move toward sustainability. Sustainability planning initiatives that are process-based with heavy involvement of stakeholders naturally have an education component that may not require measurement. Nonetheless, there is arguably value in viewing education as a tool in itself for achieving sustainability, in which case there would be value in developing specific education initiatives to achieve certain goals, and measuring how well these initiatives are achieving such predetermined goals. Education is a potentially powerful tool for cultivating collective behaviors that support sustainability. Also generally absent from the indicator systems are factors influencing or otherwise impacting the security of transportation and other infrastructure systems, also a critical element of infrastructure system sustainability. Security is used here to refer to the vulnerability and survivability of infrastructure systems in various attack scenarios.

It also worth noting that not all the indicator systems have both input and output indicators in every dimension (i.e., category) of indicators. Where any particular dimension is heavily output-oriented, this is an indication that little is being done to track and influence actual actions and/or activities that affect sustainability in any particular dimension. If such actions and activities were outside the responsibility or mission of the responsible agency, then it would seem logical that the agency has chosen to focus only on outputs in this dimension, in the short term. Otherwise, there would be value in identifying and including input indicators and defining associated policies and procedures to directly or indirectly affect progress toward sustainability.

It is also generally the case that the indicator systems do not attempt to separate out higher-impact indicators and metrics from lower-impact ones. A paper by Bannister and Pucher (2003) identifies and discusses critical-impact areas for attaining sustainability in transportation systems. Beginning to prioritize factors for evaluating sustainability according to their relative potential for moving jurisdictions forward toward sustainability would be a useful step forward in the development of systematic approaches for evaluating sustainability in infrastructure systems.

2.2. Evaluation Methodologies -- Sustainable Transportation

A growing number of qualitative and quantitative studies on assessing transportation system sustainability have been conducted around the world. As with the definitions and performance measures of sustainability, however, no standard model or evaluation methodology can be found. This section synthesizes major emergent methodologies that can be applied for practical modeling of transportation sustainability within regional planning. The literature proposes various tools and methodologies such as scenario planning; graphical models; system dynamics approaches; economic-based models; integrated transportation and land use models; simulation and decision analysis models; environmental impact analysis; and life cycle assessment (LCA). The intent in presenting these models is to provide some context on the analytical tools used in conjunction with the indicator frameworks to assess sustainability in planning.

Scenario planning approaches essentially incorporate uncertainties associated with key drivers, such as population, employment, and travel demand, in planning. The transportation planning process may incorporate scenario analysis that explores a list of reasonable options/scenarios to address various sustainability issues such as environmental integrity, safety, and mobility. Since the standard methodology of scenario assessment, based on the benefit-cost framework, has failed to investigate cause-and-effect relationships within and affecting transportation systems, the system dynamics approach has been proposed to investigate the cause-and-effect relationships between state and flow variables organized in feedback loops within an integrated system. Influence diagrams, one of the most relevant methodologies among graphical models, also capture the dependency structure among events and factors. The wide range of factors influencing the conditions of sustainability, such as market forces, low-price fuel, and vehicle-dependent land use patterns, can be identified and used in the analysis.

Quantitative sustainability models have been applied in several European studies, including such models as SPARTACUS (Systems for Planning and Research in Towns and Cities for Urban Sustainability) and ESCOT (Economic Assessment of Sustainability Policies of Transport) initiatives. The SPARTACUS study uses an integrated transportation and land use model, MEPLAN, in order to evaluate the sustainability of selected transportation and land use scenarios. The transportation and land use interaction model captures how the degree of access (accessibility) provided by the transportation system can influence land use distribution, and, in turn, how the spacing of development can greatly influence regional travel patterns. The ESCOT study, on the other hand, focuses more on evaluating the "economic" feasibility of environmentally sustainable scenarios using a system dynamics model. Emerging methods of evaluating sustainability are based on the comprehensive concept of sustainability, defined earlier as including economic, environmental, and social parameters of sustainability, incorporating various types of integrated transportation - land use - environment models.

The Federal Highway Administration (FHWA) under the United States Department of Transportation has developed a toolbox for regional policy. The toolbox is designed for use by metropolitan planning organizations (MPOs), state departments of transportation (DOTs), and other analysts would like to assess a range of impacts in regional transportation and/or land use planning. Through a number of case studies in U.S., the toolbox summarizes different analytical methods for testing the regional impacts of transportation and land use policies in contrast to project-level analysis techniques. While the toolbox itself does not explicitly address "sustainability" impacts, impacts of interest include economic development, environmental justice, accessibility, land development, wetland and habitat impacts, and other social and environmental measures associated with transportation investments and land use policies (FHWA, 2004).

Another good example of a quantitative application may be found in Zietsman et al. (2003). Zietsman et al.'s simulation and decision model provides important insights for the integration of a sustainability evaluation process with a decision making process. The authors develop a single index for sustainable transportation from selected performance measures based on the multi-attribute utility theory (MAUT) technique. While these researchers mainly focus on quantifying the sustainability of selected corridor-level scenarios using a microscopic simulation model, CORSIM, the application of a multiple criteria decision making (MCDM) approach in the sustainability evaluation demonstrates the benefits of using indexes and is broadly applicable (Zietsman et al., 2003).

2.2.1. Synthesis – Tools and Techniques

The review of analytical methods for sustainability evaluation reveals that while there is no standard method, there are several important elements to consider in the development of robust methodologies for sustainability evaluation. These critical elements are discussed below.

1) The analysis methods that can capture both *causal* and *impact* elements of sustainability (e.g., those that incorporate systems dynamics or graphical models) will typically present a broader systems view of the infrastructure system under consideration, and enable the analyst to identify and consider the key drivers that affect the sustainability of the system under consideration, to the extent that this is possible. Methodologies that are limited to the impacts of the system fail to capture these key components of system sustainability (i.e., the causal factors) and hence do not directly address the policy elements that can influence change during the modeling stages of the planning process. Hence, ideally, the policy elements must be addressed explicitly at some other stage during the planning process.
2) Along similar lines, analysis methods that capture the land use/transportation interaction are expected to provide more robust results in comparison with methods that are based on the traditional transportation planning models that do not explicitly address the critical and intrinsic land use element which is a key influence in determining the relative sustainability of a transportation system.
3) Most models are based on the multidimensional themes of economic, environmental, and social impacts, indicating that a robust method should at the minimum consider these dimensions as decision making criteria. This would seem to indicate that multicriteria/multiobjective methods are better suited to sustainability assessments than single-criterion/single objective methods.

4) The uncertainties inherent in the planning process may be addressed by introducing scenario methods which in essence postulate plausible scenarios based on key system drivers, and then proceed to develop plans that would ensure acceptable outcomes for all the plausible scenarios. Because of the uncertainties associated with planning, particularly in the context of rapid metropolitan growth and the proliferation of major and megacities, it would seem that such a construct would become integral element of transportation planning to inject robustness into the process.
5) While not directly distilled from the literature, a more comprehensive effort at sustainability planning for transportation should involve other modes than the highway system. In particular, for regions with public transit options, frameworks that allow multiple modes to be considered should produce more useful results with reference to moving the region toward sustainability.
6) A truly sustainability-oriented analysis should consider accessibility as well as mobility to properly integrate land use considerations.
7) A truly sustainability-oriented analysis should also incorporate the systems interactions not only among the causal factors influencing sustainability but the impacts as well. In other words, the economy, social equity, and the environment are not entirely isolated and a complete analysis ought to capture the interactions among these three domains of sustainability.
8) Emerging analytical approaches for sustainable transportation tend to incorporate more integrative models or software suites which allow the analyst to evaluate a wider range of sustainability issues. Ideally, sustainability evaluation should

incorporate broader environmental, economic, social impacts of transportation systems and model the necessary interactions among these multi-dimensions.

These eight critical elements were important guiding principles in framing the methodology developed for the evaluation, and can be considered as important guiding principles in general in the development of analysis tools for sustainability assessment (Jeon et al., 2008).

2.3. Multiple Criteria Decision Making in Transportation

The multidimensional nature of sustainability indicates that multicriteria or multiobjective methods would be more appropriate for sustainability assessments than single-criterion/single-objective methods. This section first reviews multiple criteria decision making (MCDM) methods in general and identifies a number of MCDM applications to transportation planning decision making.

2.3.1. Multi-Criteria Decision Making (MCDM) Method

Multi-criteria decision making (MCDM) is one of the established branches of Decision Theory, and it is especially useful when making preference-based decisions over available alternatives that are characterized by multiple, usually conflicting, attributes (Hwang and Yoon, 1981; Triantaphyllou, 2000) Unlike single-objective decision-making techniques, such as benefit-cost or cost-effectiveness analysis, MCDM approaches can take into account a wide range of differing, yet relevant criteria (Zietsman et al., 2003). Even though these criteria cannot always be expressed in monetary terms, as is the case with many externalities, comparisons can still be based on relative priorities (Nijkamp and Van Delft, 1977).

MCDM methods are generally divided into (1) multi-objective decision making (MODM) that studies decision problems with a *continuous* decision space and (2) multi-attribute decision making (MADM). In many cases, the terms MADM and MCDM are used interchangeably, and they concentrate on problems with a *discrete* decision space (Triantaphyllou 2000). MCDM methods are widely diverse. Chen and Hwang (1991) classified a group of MCDM methods according to the type of information and the salient features of information received from the decision maker (See Figure 7). The weighted sum model (WSM), the weighted product model (WPM), and the analytic hierarchy process (AHP) method are the most commonly used MCDM methods.

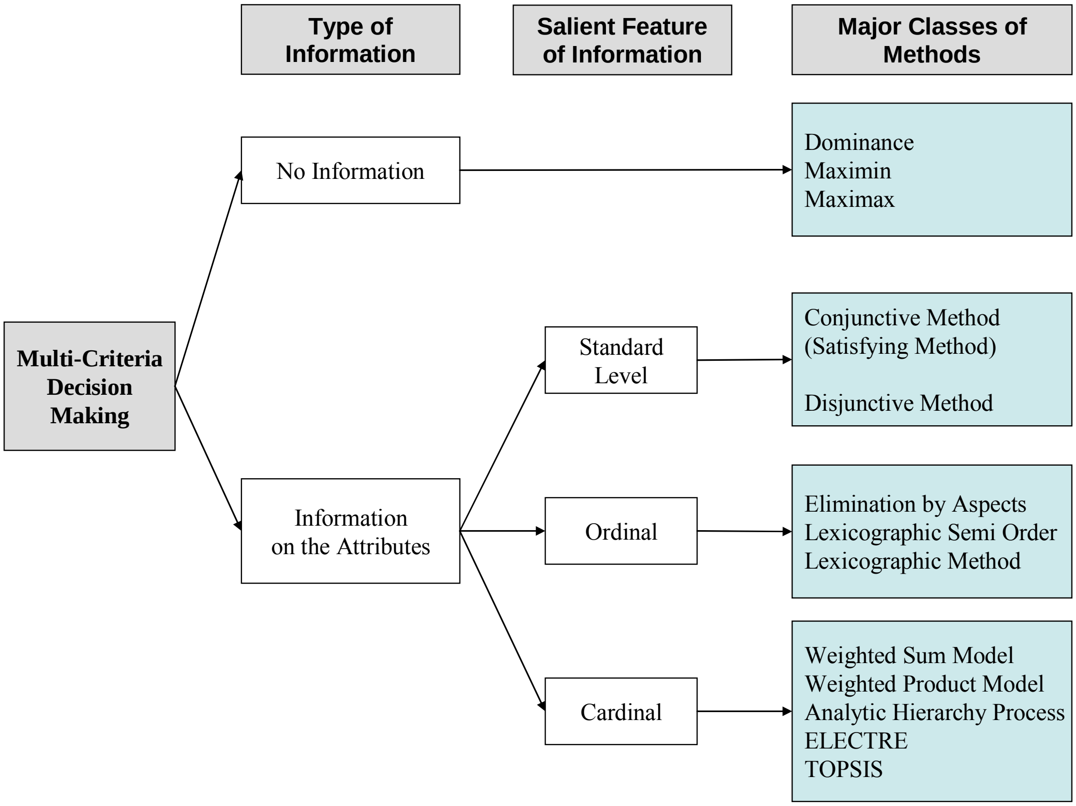

Figure 7 A Taxonomy of MCDM Methods (Chen and Hwang, 1991)

MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) is a relatively new methodology used in multi-criteria decision aids, developed in the early 1990s by Bana e Costa and Vansnick (2003). MACBETH utilizes one of the most common MCDM techniques, the weighted sum model (WSM), which employs an additive value aggregation model. In addition, MACBETH's interactive approach requires only qualitative judgments about differences to help a decision maker quantify the relative attractiveness of options. It employs an initial, interactive, questioning procedure that compares two elements at a time, requesting only a qualitative preference judgment. As judgments are entered into the software, it automatically verifies their consistency. A numerical scale is generated that is entirely consistent with all the decision maker's judgments. Through a similar process weights are generated for criteria. The M-MACBETH software provides tools to facilitate: complete model structuring, management of complex problems involving qualitative value scores and weights, and interactive sensitivity and robustness analyses (Bana e Costa, 2003).

This study also employs the weighted sum model (WSM) as with the MACBETH method. The WSM approach is used interchangeably with the additive utility model which has various strengths over the other methods. This model is particularly simple, it is well known, its technical parameters have a clear and explicable substantive interpretation, it allows processing of the difficult problem of the relative importance of criteria in a precise way, and it permits avoidance of the difficulties that are inherent in every ordinal aggregation (Bana e Costa, 2003).

2.3.2. MCDM Applications in Transportation

Because the transportation planning process includes many different objectives and reflects the interests of a wide range of stakeholders, appropriate techniques need to incorporate these multiple and conflicting objectives into the assessment process. Moreover, decision-making in the context of sustainable transportation should involve the evaluation of a discrete set of alternatives while simultaneously considering conflicting objectives. This section identifies relevant international studies that apply different MCDM methods to metropolitan transportation planning and decision making.

As early as 1980, Black and Kuranami introduced interactive multiple objective programming in the field of strategic land use and transportation planning as a promising method of helping decision makers examine competing objectives (Black and Kuranami, 1980). Since then, an increasing number of international studies have discussed different MCDM methods to address transportation-related problems. These studies mainly aim to investigate and evaluate relevant multidimensional impacts of transportation projects, programs, or policies with complementing conventional (single-objective) cost-benefit analysis. Most of these studies can be categorized as project-level studies which focus on evaluating competing transportation improvement projects (Aboul-Ela et al., 1982; Gomes, 1989; Tabucanon and Lee, 1995; Zografos et al., 1997; Schwartz et al., 1998; Hsu, 1999; Leviakangas and Lahesmaa, 2002; Vreeker et al., 2002; Reza Ghaeli et al., 2003; Li and Sinha, 2004; Ertugrul Karsak and Sebnem Ahiska, 2005). Several studies can be categorized as corridor-level analyses (Zietsman et al., 2003; Filippo et al., 2007) and others can be classified as system-level or policy-level analyses (Tsamboulas and Kopsacheili, 2003; Latuso et al., 2004; Tanadtang et al., 2005; Zhang et al., 2005).

The research trends indicate that MCDM methods have been often applied to project-level studies since the early 1980s. MCDM applications to broader scope analyses, such as the evaluation of transportation plans or policies, are more recent research trends that seem to have been propagated in the literature since 2003. One of the most common methodologies of MCDM is Saaty's Analytic Hierarchy Process (AHP) developed in 1970s to provide a systematic approach to setting priorities and decision making based on pairwise comparisons between criteria (Saaty, 1995). Since Saaty introduces the application of this method in transportation decision making, the AHP method is frequently used to incorporate multiple decision criteria in the evaluation of transportation alternatives. Another recent trend includes an embracement of different types of "fuzzy" multicriteria decision making approaches. These fuzzy-type MCDM methods attempt to cater for uncertainty, vagueness, or fuzziness commonly inherent in human decision making due to a lack of information or constraints in human thinking. Some other initiatives make progress by combining the AHP method with different types of fuzzy MCDM methods. The following two paragraphs describe some examples of relevant studies that apply the AHP method and fuzzy-type MCDM methods, respectively, in transportation decision making.

Tabucanon and Lee (1995) apply the AHP method to evaluate rural highway improvement projects in Korea and demonstrate that the AHP could be an effective tool in evaluating transportation system projects. Hsu (1999) combines the AHP method with a fuzzy Delphi method to develop a group decision model – a Fuzzy Delphi Analytic Hierarchy Process (FDAHP). The author applies the FDAHP method to the evaluation of the mass rapid transit system and the bus system in Kaohsiung, Taiwan. Latuso et al.

(2004) evaluate integrated land use and transportation policies in order to find sustainable long-term urban strategies and to demonstrate their effects in European cities. The researchers assess a set of indicators for environmental, social, and economic dimensions of urban sustainability and propose several sustainability indexes using the AHP method. Tanadtang et al. (2005) evaluate transportation demand management (TDM) alternatives using the AHP method and evidential reasoning (ER) approach based on Decision Theory and Dempster-Shafer Theory of Evidence. Zhang et al. (2005) evaluate the highway transportation sustainable development of Tianjin city, applying the fuzzy identification theory and AHP method.

Aboul-Ela et al. (1982) evaluate the alternatives proposed to improve the transportation system from mainland Canada to Newfoundland based on the use of fuzzy sets and another evaluation theory. Ertugrul Karsak and Sebnem Ahiska (2005) evaluate transportation alternatives using a robust two-phase fuzzy decision framework, which integrates the fuzzy Delphi method and a hierarchical distance-based fuzzy multicriteria decision making (MCDM) approach. Lee and Chou (2006) evaluate airline competitiveness over a period using fuzzy multiple criteria decision making model. Bell (2006) extends the decision framework in transportation to encompass multiple objectives by synthesis with the Bellman-Zadeh fuzzy decision principle. Filippo et al. (2007) present a procedure for ranking environmentally valid highway restoration by priority, using a Fuzzy Multi-Criteria Model that supports decisions on which road segments require these works and services.

The most common MCDM schemes include the weighted sum model (WSM), the weighted product model (WPM), and the analytic hierarchy process (AHP). A recent update of literature review indicates that different types of fuzzy MCDM methods are more frequently used in transportation decision making to confront uncertainties. These fuzzy-type MCDM methods attempt to cater for uncertainty, vagueness, or fuzziness commonly inherent in human decision making due to a lack of information or constraints in human thinking. Some other initiatives make progress by combining the AHP method with different types of fuzzy MCDM methods. MCDM applications to broader scope analyses such as the evaluation of transportation plans or policies, in contrast to the evaluation of transportation projects, are another recent trend that seems to have been propagated.

2.4. Synthesis

The literature review findings indicate that while there is no standard definition for transportation sustainability, there seems to be emerging consensus that, in order to be effective, it must include impacts on the economy, environment, and social well-being; it must address the *causes* of sustainable or non-sustainable trends; it must consider the *relative levels of influence* that oversight agencies have with respect to implementing policies and procedures that impact sustainability; and it must have a strong stakeholder component. The existing indicator systems reveal that operationally, transportation sustainability is largely being measured by transportation system effectiveness and efficiency as well as the environmental impacts of the system.

At the same time, a growing number of qualitative/quantitative studies on modeling transportation system sustainability have been conducted around the world. As with the definitions and performance measures of sustainability, no standard model or evaluation methodology is found. Qualitative sustainability models include scenario planning approaches that essentially incorporate uncertainties associated with key drivers, such as population, employment, and travel demand, into sustainability planning. System dynamics approaches and influence diagrams are occasionally used to investigate the cause-and-effect relationships within sustainable transportation systems. Quantitative sustainability models have been introduced in several European studies, in an integrative toolbox developed by Federal Highway Administration (FHWA) under the United States Department of Transportation, as well as in Zietsman et al.'s simulation and decision analysis model. The SPARTACUS study uses an integrated transportation and land use model, MEPLAN, in order to evaluate the comprehensive sustainability of selected transportation and land use scenarios. The ESCOT study, on the other hand, focuses more on evaluating "economic" feasibility of environmentally sustainable scenarios using a system dynamics model. Emerging trends of modeling sustainability are evaluations of a broader concept of sustainability, defined earlier as economic, environmental, and social sustainability, incorporating various types of integrated transportation - land use - environment models. The FHWA toolbox is designed for use by metropolitan planning organizations (MPOs), state departments of transportation (DOTs), and other analysts would like to assess a range of impacts in regional transportation and/or land use planning. While the toolbox itself does not explicitly address "sustainability" impacts, impacts of interest include economic development, environmental justice, accessibility, land development, wetland and habitat impacts, and other social and environmental measures associated with transportation investments and land use policies (FHWA, 2004). Zietsman et al.'s simulation and decision analysis model provides important insight for the combination of a sustainability evaluation process with a decision making process. While these researchers mainly focus on quantifying the sustainability of selected project-level scenarios using a microscopic simulation model, CORSIM, the application of a multiple criteria decision making (MCDM) approach in the sustainability evaluation framework is broadly applicable.

Most analytical models of sustainability are based on the multidimensional themes of economic, environmental, and social impacts, indicating that a robust method should at the minimum consider these dimensions as decision making criteria. Thus, multicriteria/multiobjective methods seem to be better suited to sustainability assessments than single-criterion/single objective methods. Common multiple criteria decision making (MCDM) methods were first reviewed in general, and their applications to transportation planning and decision making identified. This study uses the weighted sum model because this model is particularly simple and offers transparency in the interpretation of parameters. The following chapters demonstrate an application of the multiple criteria decision making (MCDM) approach for evaluating competing transportation and land use plans and identifying superior alternatives.

CHAPTER 3

CASE STUDIES ON SUSTAINABILITY ISSUES

The case studies presented in this chapter were first reported in Jeon et al. (2006). Below much of the material is reported as presented in the paper and a discussion follows to highlight the relevance of these case studies to this dissertation.

While sustainable transportation is a policy objective or issue of concern in high-income, middle-income, and low-income countries, critical factors influencing the attainment of a sustainable transportation/land use system, the relative priorities accorded various sustainability objectives, and the constraints to be encountered in moving transportation systems toward sustainability, may be different in these different environments. Discussions on sustainable transportation that remain at a relatively general level may not shed adequate light on unique issues and priorities that must be addressed relative to attaining sustainable transportation in different socioeconomic contexts. More detailed assessments are necessary to understand better the drivers of existing transportation systems, as well as priorities and constraints for attaining sustainable transportation across the range of socioeconomic conditions in the global community.

The objective of this case study is to characterize some of the major issues in transportation sustainability in high-income, middle-income, and low-income economies. This is done through the development of four case studies for selected countries/states with a range of economic conditions: Georgia (United States, high-income status), South Korea (East Asia, recently moved from middle to high-income status), Colombia (South America, middle-income status) and Ghana (West Africa, low-income status). The purpose is threefold. First, it is to demonstrate that while definitions of sustainable transportation seem to revolve around system effectiveness and efficiency, safe and equitable access, economic development, and environmental integrity, the actual process of addressing sustainability in transportation systems and services provision may involve widely different priorities, standards, and constraints. Second, it is to emphasize that there are no universal drivers and so indicator systems for transportation sustainability and that the relative effectiveness of any indicator system is a function of how well it monitors progress toward the particular vision and standards it was intended to support. Third, it is to show that the development of definitions, visions, and indicators systems are useful starting points yet incomplete endeavors in any formal approach to consider sustainability in transportation planning. Gudmundsson emphasizes this need to link indicator systems with actual policies basin a study that evaluates six sustainability indicator systems (Gudmundsson, 2003). Given the widely different pressures, socioeconomic conditions, and institutional constraints that exist in different contexts, adopting visions and indicators without explicitly identifying, implementing, and monitoring realistic policies to promote movement toward these visions would at best have limited effectiveness.

The next section presents four case studies for countries/states with very different socioeconomic, political, and institutional contexts to characterize major issues relative to achieving transportation sustainability, and the local contexts in which progress toward sustainability must occur. The discussion that follows highlights the importance of developing specific priorities, policies, and standards to address transportation sustainability based on a system-level understanding of the socioeconomic, political, and institutional contexts of the country or other jurisdiction under consideration.

3.1. Major Issues on Transportation Sustainability

Because the quality of transportation affects and is affected by the economy, priorities, standards, and constraints for sustainable transportation may differ, sometimes significantly, depending on the level of socioeconomic development in a country. The World Bank classifies countries as high-income, middle-income or low-income based on their gross national income (GNI) per capita. GNI (formerly Gross National Product or GNP) is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (Nationmaster.com Homepage). According to the World Bank Classification (2002), low-income economies are defined as those having a per capita GNI per of less than $735; lower-middle-income countries: $736 - $2,935; upper-middle-income: $2,936 - $9,075; and high-income countries: more than $9,076 per capita. Low-income and middle-income economies are sometimes referred to as developing economies, while high-income economies are referred to as developed economies. While the GNI, a broad measure, is considered to be the best single indicator of economic capacity and progress, it is recognized that the GNI does not by itself constitute or measure welfare or success in development (The World Bank Group Homepage).

Below, four case studies highlight the status of transportation in various economies: the state of Georgia (United States) [High-Income]; South Korea (East Asia) [High-Income/Recently Middle-Income]; Colombia (South America) [Middle-Income], and Ghana (West Africa) [Low-Income]. These cases were selected to cover the range of economic categories given by the World Bank Classification. Backgrounds of the research team were also relevant in selecting the particular geographic locations as they considered it important to have first-hand knowledge of the systems in each case. The state of Georgia was selected rather than the entire United States for comparability with the other cases, based on population and physical size. While the cases are by no means exhaustive, every attempt was made to ensure that the data, obtained from secondary sources, adequately represent the systems.

3.1.1. Georgia (United States)

Georgia is a state in the southern United States (U.S), the world's fourth largest nation in land area (after Russia, Canada, and China), extending from the Atlantic coast to the Pacific Ocean and sharing land borders with Canada in the north and Mexico in the south (About, Inc. Homepage). The country has fifty locally-autonomous states with a total population of 290 million (2004), and a per capita GNI of USD 33,684 (2003) (Nationmaster.com Homepage). It has the second largest (after the European Union) and most technologically advanced economy in the world. U.S. firms are at or near the forefront in technological advances, especially in computer, medical, aerospace, and military equipment. Although the country has rich mineral resources and various agricultural products, the biggest sector is service industries, employing about 75% of U.S. residents.

With a land area of 57,906 square miles (149,976 km^2), Georgia is the largest state east of the Mississippi River (24th overall). Atlanta, the state’s capital, is the largest city followed by Savannah, one of the busiest ports in the U.S. Based on the 2000 census, the population of Georgia was just over 8 million, making it the 10th most populous state. Nearly half of the state's population lives in the Atlanta metropolitan area, which has experienced phenomenal growth in the past decade. From 1990-2000, Georgia's population grew by over 20 percent, as shown in Table 6. Georgia's 1999 total gross state product of $275 billion placed it at 10th in the nation, and its per capita personal income of $28,145 placed it at 23rd in the nation in 2000. Service sector employment accounted for about 26% of the state's jobs, followed by retail with about 18% and government with about 15%. The state's industrial outputs are textiles and apparel, transportation equipment, food processing, paper products, chemical products, electric equipment, and tourism. Agriculture also plays a major role in the state's economy, contributing about five billion dollars annually (Wikipedia Homepage).

3.1.1.1. General Characteristics

As in several metropolitan areas around the world, the automobile is the dominant mode of transportation in the Atlanta Metropolitan Area. In 2002, the Atlanta Regional Commission (ARC), the region's Metropolitan Planning Organization, recorded a mode share of home-based work trips at 91.78%, with single occupancy vehicle share at 80.72%, carpool share at 11.06%, and public transit share at 8.22% (ARC, 2002). Highways are thus the predominant infrastructure for transportation. In 2002, Georgia's transportation system encompassed 113,655 miles (182,910 km) of public roads, 4,853 miles (7,810 km) of railroad, 103 publicly owned airports, and four shipping ports. Georgia is also served by twelve urban transit systems including the Metropolitan Atlanta Rapid Transit Authority (MARTA) that serves Atlanta and 82 rural transit systems (GDOT, 2002).

Table 6 Population and Vehicle Ownership in Georgia, U.S., 1990-2002

Year	Population		Vehicle	
	Number (thousands)	Annual Increase	Number (thousands)	Annual Increase
1930	2,908,506	-	NA	-
1940	3,123,723	7.40%	NA	NA
1950	3,444,578	10.27%	NA	NA
1960	3,943,116	14.47%	NA	NA
1970	4,589,575	16.39%	NA	NA
1980	5,463,105	19.03%	NA	NA
1990	6,478,216	18.58%	NA	NA
1991	6,621,279	2.21%	NA	NA
1992	6,759,474	2.09%	NA	NA
1993	6,894,092	1.99%	NA	NA
1994	7,045,900	2.20%	NA	NA
1995	7,188,538	2.02%	6,192,515	NA
1996	7,332,225	2.00%	6,356,164	2.64%
1997	7,486,094	2.10%	6,317,832	-0.60%
1998	7,636,522	2.01%	6,979,592	10.47%
1999	7,788,240	1.99%	7,059,719	1.15%
2000	8,186,453	5.11%	7,243,077	2.60%
2001	-	21.60% (1990-2000)	7,396,731	2.12%

Data adapted from the Intermodal Transportation Database Homepage and U.S. Census Bureau Homepage

Like several metropolitan areas around the world, Metro Atlanta faces severe congestion, with the associated air quality and respiratory health issues. Rapid population and a booming economy have contributed to increasing traffic congestion and reduced air quality in the Metro Area. To control traffic congestion and air pollution, Georgia Department of Transportation (GDOT) has developed a high-tech intelligent transportation system (ITS): the NAVIGATOR, which monitors more than over 200 miles of highway through the use of state-of-the-art video cameras, changeable message signs, and data management technologies to relay real-time traffic conditions 24 hours a day to a Transportation Management Center (TMC). Complementing the system is GDOT's network of highway emergency response operators (HERO): incident response units with specially trained personnel who can deal quickly with accidents and disabled vehicles. HEROs are important not only for their emergency services but for congestion management as well because in Metro Atlanta, while slightly under half (48%) of the congestion delay is normal recurring (volume-related), slightly over half (52%) is from non-recurring (incident-related) delay. Other measures to manage congestion include 90 miles of high occupancy vehicle (HOV) lanes, 88 park and ride lots, and 2,943 miles of bicycle and pedestrian routes (GDOT Homepage, 2005).

3.1.1.2. System Effectiveness

Approximately half of Georgia's population, 50% of the vehicle miles traveled (VMT), and 75% of the congestion in the state occur in Metro Atlanta (GDOT, 2001). Vehicle ownership in the state has continued to rise since the mid-90s, as shown in Table 7. The resulting roadway congestion and traffic delay have been estimated to cost Metro Atlantans 101 million person-hours of delay every year, equating to $2 billion in total delay costs annually. According to the Texas Transportation Institute (TTI), the travel time index (traffic delay and congestion costs) has increased over 26% in the past 8 years and Metro Atlanta has the 11th most congested freeway system in the U.S. (TTI Homepage). At the same time, VMT in Georgia has been growing rapidly at an annual rate of 3.4% since 1990 and has approximately doubled during the past two decades. Accommodating this rapid growth by maintaining a first class roadway network and providing transportation choices has been and will continue to be the major challenge facing the State (GDOT Homepage). Rapid population growth and urban sprawl have exacerbated the congestion problem. Despite Georgia's growing population and dependence on automobile transportation, the state's transit systems have been utilized at a declining rate per capita in the past 10 years (ASCE Homepage). Compared with the rest of the country, Georgia's per capita transit system usage is below the national average. Table 8 depicts the decreases in transit ridership and transit system effectiveness for urban and rural transit systems in Georgia between 2000 and 2002.

Table 7 Vehicle Miles Traveled and Motor Vehicle Crashes, Georgia, 1990-2002

Year	Millions VMT (VKT)	Annual Increase Rate	Crashes Number	Fatalities and Injuries (Person)			
				Fatalities (per 100million VMT)		Injuries	Total
1990	72,648 (116,916)		228,163	1,564	2.15	98,933	100,497
1991	72,937 (117,381)	0.4%	218,766	1,393	1.91	96,748	98,141
1992	77,569 (124,835)	6.4%	231,122	1,324	1.71	102,951	104,275
1993	77,886 (125,345)	0.4%	242,093	1,407	1.81	109,350	110,757
1994	82,780 (133,221)	6.3%	270,688	1,437	1.74	135,731	137,168
1995	85,280 (137,245)	3.0%	283,639	1,492	1.75	139,857	141,349
1996	88,888 (143,051)	4.2%	298,247	1,582	1.78	142,864	144,446
1997	93,268 (150,100)	5.0%	301,767	1,584	1.70	139,386	140,970
1998	96,607 (155,474)	3.6%	293,251	1,579	1.63	133,034	134,613
1999	98,913 (159,185)	2.4%	-	1,514	1.53	-	-
2000	104,723 (168,535)	5.9%	309,334	1,548	1.48	127,177	128,725
2001	107,974 (173,767)	3.1%	317,851	1,621	1.50	129,431	131,052
2002	108,300 (174,292)	0.3%	328,272	1,532	1.41	132,913	134,445

Data adapted from Georgia Department of Public Safety Homepage and GDOT Homepage

3.1.1.3. Safety

The safety of Georgia's roads is average, relative to other U.S. states. There were 1,621 fatalities in 2002, which translates to a fatality rate of 1.50 fatalities per 100 million VMT (the U.S. average is 1.51 fatalities per 100 million VMT) (GDOT 2001). Trends in VMT and the relative number of crashes, fatalities, and injuries, show that safety has been steadily improving over the past decade. However, a considerable portion of the state's fatality crashes have occurred on rural roads, especially on two-way roads, making highway safety in rural areas a major issue in the state. Based on 2001 statistics, 4 out of 10 crash deaths occurred on rural roads, and 7 out of 10 fatalities occurred on two-way roads without any physical separation or barrier (Governor's Office of Highway Safety Homepage)

Table 8 Georgia Urban and Rural Transit System Ridership, 2000-2002

		FY 2000		FY 2002	
		Ridership (Population)	Effectiveness*	Ridership (Population)	Effectiveness
Urban Transit System	All but MARTA	12,856,803 (2,535,590)	5.1	13,006,678 (2,629,114)	4.9
	MARTA	166,915,560 (1,458,484)	114.4	159,145,301 (1,457,372)	109.2
	Sub Total	179,772,363 (3,994,074)	45.0	171,853,917 (4,086,486)	42.1
Rural Transit System		1,680,049 (4,192,479)	0.4	1,642,655 (4,473,824)	0.3
Total		181,452,412 (8,186,453)	22.2	173,496,572 (8,560,310)	20.3

* The effectiveness of these transit systems is calculated by dividing ridership by population.
Data adapted from Georgia Department of Transportation (2003), Georgia Department of Transportation Homepage, and U.S. Census Bureau Homepage

3.1.1.4. Congestion/Air Quality

Atlanta is currently designated as a non-attainment area for ozone and will be designated as a non-attainment area for particulate matter out of the six pollutants for which the Clean Air Act (CAA) establishes standards (ASCE 2003). As shown in Table 9, Georgia ranks relatively high for statewide anthropogenic emissions. In the past several years, however, there have been reductions in the number of ozone exceedance days in Atlanta from a high of 23, which occurred in 1999 to a low of 1, which occurred in 2003, as shown in Table 10. Various measures have been taken to aid in controlling the precursors to ozone formation, including a strict vehicle inspection program, controls on emission sources, and the establishment of a voluntary pollution outreach program called the Clean Air Campaign (AAA and Georgia Regional Transportation Authority 2002).

Table 9 Georgia Statewide Anthropogenic Emissions and Rank, 1998

Emissions	CO	NOx	VOC	SO2	PM10	PM2.5	NH3
Thousands short tons	3,998	730	576	660	1,103	320	106
Rank out of the51 states	4	12	9	13	7	4	17

Data adapted from U.S. EPA (2000)

Table 10 Exceedances of Federal Air Quality Standards in Georgia (Atlanta)

	Ozone 8 hour-avg. (O3 ppmv)	**Ozone 1 hour-avg. (O3 ppmv)***	**Sulfur Dioxide (SO2 ppmv)**
1996	0	7 (7)	0
1997	0	12 (11)	0
1998	120 (62)	24 (22)	9
1999	129 (69)	28 (23)	0
2000	101 (46)	16 (11)	0
2001	40 (20)	5 (3)	1
2002	64 (37)	8 (8)	0
2003	23 (13)	1 (1)	0

*EPA recently revised the ozone standard for areas of the state that are outside the Atlanta non-attainment area. For these areas, the 1-hour ozone standard was replaced with an 8-hour average ozone standard. Data adapted from Georgia Department of Natural Resources Homepage

3.1.1.5. Social Equity/Other Issues

Social equity issues in transportation include equitable access to major social and economic centers for all Georgia's residents, as well as equitable levels of safety on the urban and rural portions of Georgia's highway system. Following a federal executive order (EO 12898) in 1994 for addressing equity (environmental justice) in the decision making process, GDOT has taken several measures to improve capabilities for addressing equity in transportation planning. Environmental justice is part of the Department's planning process and project development considerations. GDOT is in the process of developing a template for planning and project evaluations that will measure, among other things, the benefits and burdens of transportation projects on low income and racial minority communities (GDOT Homepage).

3.1.1.6. Transportation/Land Use Decision Making

Federal and state laws require that the State's transportation program align with a long-range strategy in the *Statewide Transportation Plan* developed by the State Department of Transportation. This plan is updated every five years and maintains a minimum 20-year horizon. As the federally designated Metropolitan Planning Organization (MPO) for the Atlanta region, the Atlanta Regional Commission (ARC) is responsible for developing a long-range Regional Transportation Plan for the 10-county Metro Atlanta region where nearly half of the state's population resides. The State Department of Community Affairs (DCA) develops a regional comprehensive plan and land use regulations through a "bottom-up" process that is based on the plans of local jurisdictions. DCA's planning staff is also working with ARC staff to assist local governments in meeting the requirements for a Transportation Element which is a required part of the comprehensive plans of local governments (Georgia Department of Community Affairs Homepage). As indicated, efforts are being made in Georgia to integrate land use decisions which originate in local jurisdictions with state-level transportation planning decisions, with the intent of reducing trips and curbing environmental problems. The mission of the Georgia Regional Transportation Authority (GRTA) and the Governor's Development Council is to improve Georgia's mobility, air quality, and land use practices, to enhance the quality of life of Georgia's citizens and promote growth that can be sustained by future generations. To achieve this mission, land use practices are being identified to promote more efficient use of transportation investments and restrict choices for citizens to live, work, and play with fewer and shorter trips. Key stakeholders including GDOT, ARC, GRTA, the State Road and Tollway Authority (SRTA), have been asked by the Governor to work together to develop a common plan (Georgia Governor Sonny Perdue Homepage).

3.1.2. South Korea (East Asia)

The Republic of Korea, commonly known as South Korea, is a country located in East Asia, covering the southern half of the Korean peninsula, which spans 98,480 square km, about two-thirds the size of Georgia. To the north, the peninsula borders China and Russia through the Democratic Republic of Korea (often called North Korea), while Japan lies across East Sea to the southeast. South Korea's population, estimated at 47.6 million (2002), is one of the most ethnically and linguistically homogeneous in the world. Korea has a population density of 479 people per square km. This is more than six times the population of Georgia distributed on land mass two-thirds the size of Georgia. Seoul, the capital, is a burgeoning megacity (i.e., a city with over 10 million people). As one of the four East Asian Tigers, South Korea has achieved an incredible record of growth and integration into the high-tech modern world economy over the past 30 years. The per capita GNP, only $100 in 1963, exceeded $9,800 in 2002 (i.e., per capita GNI of USD

9,930 in 2002) and is equal to that of the lesser economies of European Union, ranking South Korea as the 12th largest economy in the world. Korea has been a major world steel producer since 1990. Also, the nation's shipbuilding and auto manufacturing industries have reached their peak while its electronics industry is the leading growth sector and an increasingly important foreign exchange generator. With a significant investment in information technology (IT), Korea's IT industry has recorded astonishing growth since the 90s, further augmenting the health of the Korean economy (Wikipedia Homepage, Korea.net Homepage).

3.1.2.1. General Characteristics

Roads, handling over 90% of the country's traffic, are the most important type of transportation infrastructure in Korea as well. The total length of the roads has tripled in the past 40 years and measured a total 96,928 km in 2003. Twenty four expressways measuring 2,778 km in all connect Seoul with provincial cities and towns, covering all parts of the country and placing any destination in Korea within a day's travel. As of 2003, there were 56 routes of national highways measuring 14,234 km in total, making up Korea's trunk road network, together with expressways, providing connections among major cities, ports, airports, and industrial areas. As of 2002, the railway system of Korea encompassed 64 routes spanning 3,129 operational kilometers. The Gyeongbu High Speed Rail, linking Seoul and Busan, the second largest city located on the southeast coast, began service in Korea in April 2004 with the operation of its first high speed train. The subway system network, composed of 12 subway lines (411.5 km), operates in Seoul and three other major cities, and six new lines extending 134.7 km are under construction. Buses and taxis play a vital role in supplementing the subway networks in medium and small cities and meeting transportation needs in the larger cities (Ministry of Construction and Transportation Homepage).

To increase the efficiency of transportation operations and improve safety using information technology, the Korean government initiated a high-tech intelligent transportation system (ITS) in 1992. Korea has implemented a freeway traffic management system (FTMS), covering 320 km of expressways, and launched a real-time control system in Seoul. The country is also making efforts to establish an integrated logistics information system for the commercial vehicle operations (CVO) component of the system.

3.1.2.2. System Effectiveness

As a result of rapid industrialization, urbanization, and economic growth, South Korea is facing serious transportation problems in its cities. Table 11 shows trends of population and vehicle ownership in Korea. Population growth is being smoothed while vehicle ownership has increased dramatically more than three times in a little over a decade from 3.4 million (1990) to 14 million (2002), owing to the steady rise in income and living standards, expansion of suburbs, and the development of the country's automobile manufacturing industry. Transit system improvements are being made to ameliorate existing conditions.

3.1.2.3. Congestion/Air Quality

The phenomenal increases in vehicular ownership and transport demand create typical urban transportation problems such as severe traffic congestion, air and noise pollution, and serious parking difficulties. Urban transportation policies in Korea are therefore in a transitional stage from a supply-oriented to demand-management focus. In addition to continued investment in urban highway networks, city governments are implementing transportation demand management (TDM) plans to control automobile traffic. First, congestion pricing was introduced at the Namsan Tunnel leading to the central business district (CBD); second, the traffic impact tax was reduced by 50% for employers who implemented TDM programs, such as carpools; third, higher parking fees have been instituted in congested areas; and fourth, exclusive bus lanes and smart-card fare collection systems have been implemented (Ministry of Construction and Transportation Homepage).

Table 11 Population and Vehicle Ownership, Korea, 1990-2002

Year	Population		Vehicle	
	Number (thousands)	Annual Increase	Number (thousands)	Annual Increase
1990	42,869	-	3,395	-
1991	43,296	1.0%	4,248	25.1%
1992	43,748	1.0%	5,231	23.1%
1993	44,195	1.0%	6,273	19.9%
1994	44,642	1.0%	7,404	18.0%
1995	45,093	1.0%	8,469	14.4%
1996	45,525	1.0%	9,553	12.8%
1997	45,954	0.9%	10,413	9.0%
1998	46,287	0.7%	10,470	0.5%
1999	46,617	0.7%	11,164	6.6%
2000	47,008	0.8%	12,059	8.0%
2001	47,343	0.7%	12,914	7.1%
2002	47,640	0.6%	13,949	8.0%
Average annual increase rate		0.9%		12.7%

Data adapted from the Ministry of Construction and Transportation Homepage

The problem of air pollution in Korea is still not very severe relative to the allowable limits set by the Ministry of Environment, as shown in Table 12. However, the levels of particulate matter and nitrogen dioxide have gradually increased because of the high growth rate of automobile ownership. Table 13 depicts the undesirable trends for carbon monoxide, nitrogen oxides, non-methane volatile organic compounds (VOCs), and sulfur dioxide emissions. All the emission levels increased from 1990 to 1995, and are assumed to still be on the rise owing to continuing growth in vehicle ownership.

Table 12 Air Pollution Trends and Standards, Korea, 1998-2002

Pollutants	1998	1999	2000	2001	2002
SO_2 (ppm)	0.009 (0.050)*	0.009 (0.050)	0.008 (0.050)	0.007 (0.020)	0.006 (0.020)
NO_2 (ppm)	0.020 (0.050)	0.023 (0.050)	0.024 (0.050)	0.025 (0.050)	0.023 (0.050)
O_3 (ppm)	0.020	0.021	0.020	0.021	0.021
CO (ppm)	1.0	1.0	0.9	0.8	0.7
PM_{10} (µg/m^3)	55 (80)	51 (80)	53 (80)	58 (70)	61 (70)
Pb (µg/m^3)	0.0959	0.0785	0.0934	0.0669 (0.5)	0.0732 (0.5)

*The values in parentheses represent the average annual limits for each pollutant.
Data adapted from Ministry of Environment (2003)

Table 13 Air Pollution Trends, Korea, 1990-1995

(Unit: Thousand metric tons)	1990	1995
CO	5234.9	6208.0
NOx	914.8	1514.9
Non methane VOC	871.1	1402.6
SO2	2429.9	3290.7

Data adapted from Earth Trend Homepage

3.1.2.4. Safety

The high rate of road traffic crashes, in conjunction with the absence of order on the road, has long been considered a critical social problem in Korea. Road traffic fatalities were the leading cause of death for people under 29 in 2003 (Yang and Kim 2003). The safety level of South Korea's roads is much lower than the average level of safety in OECD countries. As shown in Tables 14, the country saw 7,185 fatalities in 2003, a fatality rate of 4.4 per 10,000 vehicles compared with the OECD average of 1.9 fatalities per 10,000 vehicles. The major causes of traffic crashes are (1) reckless driving (64%), including drunk driving, speeding, and non-use of seatbelts, (2) violation of traffic signals (8%), (3) intrusion of median strip (7%), and (4) improper driving at intersections (7%). Compared with the 1995 levels, all three indices (crashes, fatalities, and injuries) show improvements within a relatively short time period through multiple policy interventions including enforcement of penalties for seven risky driving behaviors such as drunk driving and speeding; installation of traffic-monitoring cameras; financial rewards for citizens who reported traffic violations; and the introduction of road safety evaluation and education programs (Yang and Kim 2003).

Table 14 Motor Vehicle Crashes, Fatalities, and Injuries, South Korea

Year	Crashes		Fatalities (Person)		Injuries (Person)	
	Crashes Number	Crashes per million vehicle-km	Fatalities	Fatalities per million vehicle-km	Injuries	Injuries per million vehicle-km
1993	260,921		10,402		337,679	
1994	266,107		10,087		350,892	
1995	248,865	105.3	16,744	4.4	747,095	140.4
1996	265,052	83.1	12,653	4.0	355,962	111.6
1997	246,452	67.0	11,603	3.2	343,159	93.4
1998	239,721	75.3	9,057	2.8	340,564	107.0
1999	551,060	77.0	18,333	2.6	813,523	112.4
2000	290,481	76.5	10,236	2.7	426,984	112.4
2001	260,579		8,097		386,539	
2002	230,953		7,090		348,184	
2003	240,734		7,185		376,398	

Data adapted from Ministry of Construction and Transportation Homepage and Yang et al. (2003)

3.1.2.5. Social Equity/Other Issues

South Korea needs to address serious social problems caused by population over-concentration in Seoul and inter-regional disparities relative to access to transportation and other services, alleviate continuing environmental damage due to disorderly development, and address supply shortages and deterioration problems associated with the national infrastructures including highway, railway, seaport, airport, and freight distribution systems (Ministry of Construction and Transportation 1999).

3.1.2.6. Transportation/Land Use Decision Making

The Ministry of Construction and Transportation formulates South Korea's construction and transportation development policies to advance the national economic interest and monitors, guides, and manages multiple functions and tasks including the following: transportation policy, the Comprehensive National Territorial Plan, the land policy and management system, and housing supply and construction (Ministry of Construction and Transportation Homepage). The National Development Policy Bureau, affiliated with the Ministry of Construction and Transportation, and the Korea Research Institute for Human Settlements (KRIHS) are jointly responsible for working together to develop the Comprehensive National Territorial Plan. The Comprehensive National Territorial Plan (2000-2020) articulates five major strategies including *sustaining a healthy and pleasant environment by applying the concept of sustainable development to create a national environment management system wherein environment and development are integrated* (Ministry of Construction and Transportation 1999). In addition, a comprehensive National Transport Network Plan is developed by the Transportation Policy Office of the Ministry, whose main responsibility is coordinating national transportation policies. The most recent is the 2000-2019 Plan.

3.1.3. Colombia (South America)

The Republic of Colombia is a country in north-western South America which spans 1,138,910 square km, about seven times the size of Georgia. It is bound to the north by Panama and the Caribbean Sea, to the east by Venezuela and Brazil, to the south by Ecuador and Peru, and to the west by the Pacific Ocean. As of the 2002 Census, the population of Colombia was 43.7 million, just over five times the population of Georgia, making it the third-most populous country in Latin America, after Brazil and Mexico. The country has experienced significant population growth in the past few decades as depicted by Table 15. The per capita GNI was USD 1,820 in 2002. About 20 million people are considered to live in poverty and 10 million in extreme poverty. Movement from rural to urban areas has been heavy as has been the growth in automobiles as shown in Table 16. The urban population increased from 57% of the total population in 1951 to about 74% in 1994. Bogotá, the capital city of the Colombia, is one of the densest cities in the world, with 7.7 million people living on 35,000 hectares (350 square km). Ethnic diversity in Colombia is a result of the intermingling of indigenous Indians, Spanish colonists, and Africans. Colombia is a free market economy with major commercial and investment ties to the United States. The country is poised for moderate growth in the next several years, after recovering from a severe recession in 1999 when the Gross Domestic Product (the GDP the total market value of all goods and services produced within the borders of a nation during a specified period) fell by about 5%. The economy suffered from weak domestic demand, austere government budgets, and a difficult security situation. The current government faces economic challenges ranging from pension reform to reduction of unemployment that reached a record 20% in 1999 and may remain high, contributing to extreme inequalities in income distribution. In 1999, the share of agricultural industries stood at 19% in the overall industrial structure; manufacturing industries stood at 26%; and service industries at 55%. Two of Colombia's leading exports, oil and coffee, face an uncertain future; new exploration is needed to offset declining oil production, while coffee harvests and prices are depressed. Besides, the lack of public security is a key concern for investors who are calling for progress in the government's peace negotiations with insurgent groups (The World Bank Group Homepage, Wikipedia Homepage).

Table 15 Population Trends, Colombia, 1964-2000

Year	Population	
	Number (thousands)	Increase Rate
1964	17,484,510	
1973	20,666,920	18.20%
1985	27,853,436	34.77%
1993	33,109,840	18.87%
2000	39,685,655	19.86%

Data adapted from Department of National Statistics Homepage

Table 16 Road Traffic (Motor Vehicles in Use), Colombia, 1997-1999

Year	Passenger Cars		Buses		Goods Vehicles		Motorcycles	
1997	1,694,323		126,362		179,530		385,378	
1998	1,776,100	4.83%	131,987	4.45%	183,335	2.12%	450,283	16.84%
1999	1,803,201	1.53%	134,799	2.13%	184,495	0.63%	479,073	6.39%

Data adapted from International Road Federation Homepage

3.1.3.1. General Characteristics

Transportation mode share data indicates that about half of all trips (46%) are made by bus, 16% by taxi, 15% by automobile, 8% by pedestrian, 8% by bicycle, and 7% by motorcycle (TGI Colombia Homepage). Colombia's transportation inventory shows that the railway system of the country spanned 3,340 operational km in 2002, and highway system traversed 110,000 km (including paved and unpaved roadways) in 2000. Trains serve the densely populated areas of Colombia although service is undependable. Buses provide service between cities on the major routes while taxis offer the most reliable public transportation in cities. The country has 1,050 airports (including airports with paved and unpaved runways); the main international airports are El Dorado Airport (Bogotá) and Rafael Nunez Airport. A ferry and a boat service operate between some of the ports and cays in Colombia (World Resources Institute Homepage).

3.1.3.2. Infrastructure

The irregular terrain of Colombia makes the construction of roads and railroads costly. Urban and rural road conditions and maintenance are considered poor (Onursal and Guatam 1997, U.S. Department of State Bureau and Consular Affairs Homepage). Basic infrastructure is deteriorating in most major cities in Colombia, and the numerous construction projects initiated to improve this situation contribute significantly to congestion (World Resources Institute Homepage).

3.1.3.3. Safety

Traffic laws are sporadically followed and rarely enforced, and a traffic accident is estimated to occur every ten minutes in Colombia (U.S. Department of State Bureau and Consular Affairs Homepage). Road traffic fatalities are ranked as the second leading cause of morbidity and mortality from external causes, exceeded only by homicides. Approximately 20.2% (34,547) of all deaths recorded between 1995 and 1999 were due to road traffic injuries. Pedestrians constitute the largest category of these traffic-related casualties accounting for close to 32% of all injuries and 40% of the deaths from traffic crashes. The problem of road traffic crashes has existed predominantly in the urban areas of Bogotá, Medellin, and Cali. In these main urban centers, pedestrians constituted nearly 68% of road traffic crash victims. As shown in Table 17, over 200,000 road traffic crashes were reported in 2000, representing a four-fold increase from the crashes reported in 1986. Injuries increased four-fold from the mid-13,000s in 1986 to the mid 51,000s in 2000, while fatalities almost doubled from 3,535 in 1986 to 6,551 in 2000. This corresponds to one person dying every 80 minutes and a mortality rate of 15.2 deaths per 100,000 population (Rodriguez et al. 2003). Law enforcement is lacking in some areas resulting in the prevalence of bad driving habits and parked cars occupying public spaces such as sidewalks (Onursal and Guatam 1997).

3.1.3.4. Congestion/Air Quality

Bogotá, the capital of Colombia, is a highly congested city: the average peak-period speed on the main roads had declined to 10 km per hour or lower by 1995. Vehicle ownership is low, at one car per nine inhabitants, as is the number of cars relative to the length of the road network. About 71% of motorized trips are by bus. In addition to the high population density, congestion is to some extent due to the increasing reliance on the automobile for personal movement. Innovative policies have been implemented in Bogotá were to transform a car-centered transportation system into a people-oriented one. The goal of *TransMilenio*, the country's busway project, is to overcome the city's serious transportation problems that were the result of very rapid growth along with very rapid increase in ownership and use of automobiles. This project is based on a strategy to promote non-motorized transport, reduce car use, and increase the use of public transit (Ardila and Menckhoff 2002). Air pollution caused by motor vehicles is a major environmental problem in some parts of Colombia as in many Latin American urban centers. As shown in Table 18, the emission levels of carbon monoxide, nitrogen oxides and sulfur dioxide increased significantly from 1990 to 1995 with growth rates between 15 and 20%.

Table 17 Trends on Road Traffic Crashes, Fatalities and Injuries, Colombia, 1986-2000

Year	Fatalities	Injuries	Crashes
1986	3,535	13,449	64,289
1987	3,833	15,008	91,723
1988	5,039	19,772	117,933
1989	4,032	18,085	108,506
1990	3,704	16,086	122,112
1991	4,119	18,182	111,462
1992	4,620	21,280	130,304
1993	5,628	33,083	149,940
1994	6,989	45,940	164,202
1995	7,874	52,547	179,820
1996	7,445	50,630	187,966
1997	7,607	49,312	195,442
1998	7,595	52,965	206,283
1999	7,026	52,346	220,225
2000	6,551	51,458	231,974
TOTAL	85,597	510,143	2,282,181

Data adapted from Rodriguez et al. (2003)

Table 18 Air Pollution Trends, Colombia, 1990-1995

(Unit: Thousand metric tons)	1990	1995
CO	7052.7	7006.8
NOx	420.8	481.2
Non methane VOC	1022.3	906.1
SO2	207.4	246.3

Data adapted from Earth Trends

3.1.3.5. Transportation/Land Use Decision Making

The Ministry of Transportation is responsible for formulating the policies of the Colombian National Government in matters of transit, transportation and infrastructure. The Ministry periodically works collaboratively with the Institute of Urban Development (IDU), whose mission is to execute infrastructure maintenance and improvement projects to achieve sustainable development. The IDU monitors a transportation subsystem within an institutional framework regulated and controlled by the Ministry of Transportation. The Ministry of Transportation has also enacted Plan 2500. The most ambitious road project in the history of the Colombia, Plan 2500, will pave 2,500 km of routes in different regions in Colombia. The Ministry has gained the participation of the Ministry of Property, the National Department of Planning and the private sector economic and industrial groups led by CAMACOL, Colombia's union for industrial construction.

3.1.4. Ghana (West Africa)

The Republic of Ghana commonly known as Ghana is located in West Africa bordered to the south by the Gulf of Guinea (Atlantic Ocean), the north by Burkina Faso, the west by Cote d'Ivoire and the east by Togo. About one and half times the size of Georgia, Ghana has a total area of 239,460 square km and had a population of about 20.5 million in 2003. The per capita GNI was $270 in 2002. Ghana's population is ethnically diverse with at least 75 distinguishable languages (Encyclopedia Britannica Online Homepage). About 31% of the population is below the poverty line (Nationmaster.com Homepage). The country has a relatively high population growth rate. As shown in Table 19, the population has increased steadily over the last 25 years with 2.9 percent of average quinquennial (five-year) growth rate in the period from 1985 to 2000. About 36 percent of the population was urbanized in 2001, up from 30 percent in 1975. The country has an abundance of natural resources primarily gold, timber, industrial diamonds, bauxite, manganese, fish, rubber, and hydropower. Agriculture accounts for 45% of the GDP and cocoa and timber account for 35% of the country's exports. The GNP growth has increased steadily from 2.0% in the early 1990s to a per annum rate of 4.7% (1995-1997), with a projected growth of 4.4% through 2010. Inflation has been high in recent years with rates such as 23.6% in 2003 (U.S. Department of State Homepage); unemployment rates have also been high (20% in 1997) (IndexMundi Homepage). Accra is both the administrative and commercial center of Ghana. Its population of 1.8 million is growing at a rate of 4%, and occupies around 2% of Ghana's total area. Accra's economy contributes between 15 and 20 percent of the country's GDP, and accounts for 10% of employment in Ghana (NRTEE Homepage).

Table 19 Population and Population Growth Rates, Ghana, 1950-2000

YEAR DEMOGRAPHY	1985	1990	1995	2000	2005
Total population (000s)	12,838	15,018	17,338	19,928	22,818
Total population growth rate (%)		3.14	2.87	2.79	2.71

Data adapted from United Nations Habitat Homepage

3.1.4.1. General Characteristics

Among the major modes of transportation in the country, the road sector is of considerable importance and accounts for 94 percent of freight and 97 percent of passenger traffic (Sesime Adanu, unpublished book chapter, 2004). The country's transportation system consists of a 40,000 km road network consisting of 13,433 km of trunk roads, 24,000 km feeder roads, and over 22,000 km of urban roads; two large deep water ports, which handle about 7 million tons of import and export traffic; and a 944 km railway system serving the southern part of the country. Ghana has one international airport, and 8 regional airports and airstrips spread throughout the country (The World Bank Group Homepage). Transportation is a major source of sustenance for the Ghanaian economy. Despite its importance however, the sector is faced with several problems, such as deplorable road conditions, poor vehicular maintenance, and poor law enforcement, all of which have contributed to very high crash rates in Ghana.

3.1.4.2. Infrastructure/Equity

The poor road network is mostly seen in the disparity between rural and urban areas, where almost all the regional capitals and most of the district capitals have accessible roads while most rural areas have deplorable road conditions. The end result is that the produce, in particular major exportable perishable commodities on which the country's economy depends, can be subject to decay in the inaccessible areas, and create disincentives for farmers to produce. Not only are the roads bad, but there also exist inequalities in motorable and accessible roads in the country, attributable mainly to economic resource availability in the different areas. Lack of accessibility for vital destinations such as jobs, schools, markets, and health care has affected development activities in inaccessible areas (Sesime Adanu, unpublished book chapter, 2004). Besides, many of the roads have inadequate signs or pavement that is not equipped to handle the traffic. The country also lacks an effective public transportation system.

3.1.4.3. Safety

One of the main problems facing Ghana is increasing road traffic fatalities reflected in the number of lives lost every month. The Public Agenda newspaper (2003) revealed that 150 people die in the country every month through road accidents alone (Sesime Adanu, unpublished book chapter, 2004). According to 1994-1998 police data, road traffic crashes were a leading cause of death and injuries in Ghana, beside occupational injuries which involve non-mechanized farming and ethnic conflicts. Table 20 shows recent trends in road traffic crashes, deaths, and injuries and Table 21 shows crash and injury rates per 100,000 inhabitants. The majority of road traffic fatalities (61%) and injuries (53%) occurred on roads in rural areas. About 58 percent more people died on roads in rural areas than in urban areas, and generally more severe crashes occurred on rural roads compared with urban roads. The number of reported crashes increased by 63 percent between 1994 and 1998. Road traffic injuries increased by 49 percent and deaths by 65 percent. In the same period, the number of vehicles involved in crashes increased by 69 percent.

Table 20 in Road Traffic Crashes, Casualties, and Vehicles Involved, Ghana, 1994-1998

Year	Crashes	Fatalities	Injuries	Number of vehicles involved
1994	6,580	824	7,663	9,995
1995	8,314	1,026	9,105	12,916
1996	8,489	1,050	9,903	13,368
1997	9,914	1,014	10,431	15,619
1998	10,715	1,362	11,405	16,892
Total	44,012	5,276	48,507	68,790
% change	62.8%	65.3%	52.8%	69%

Data adapted from Afukaar et al. (2003)

Table 21 Crash and Injury Rates per 100,000 Population, Ghana 1994-1998

Region	Injury crash rate	Fatal injury rate	Serious injury rate	Slight injury rate	All casualties rate
Whole Country	139.9	28.7	102.1	161.3	292.1

Data adapted from Ghana Statistical Service Homepage

The nature of transportation-related deaths and injuries in both urban and rural areas is fundamentally different from that in developed countries: in developed countries, crashes involving occupants of private vehicles predominate and pedestrian injuries make up a smaller percentage of all transportation-related injuries (Afukaar et al. 2003). In Ghana, pedestrian deaths constitute the largest category (46%) of fatalities among all road users, followed by occupants of buses and minibuses. High driving speeds of poorly-maintained passenger-ferrying vehicles on generally badly-deteriorated roads, coupled with the lack of emergency medical services, have combined to increase fatalities on rural roads (Afukaar et al. 2003).

3.1.4.4. Congestion/Air Quality

Air quality is deteriorating in urban areas, particularly in the capital city of Accra and the surrounding metropolitan area. Ghana's urban population, especially in Accra, has burgeoned, with annual growth rates estimated as high as 4%. The corresponding rise in vehicle transportation has caused major traffic congestion and excessive wear and tear on the road network. Road travel, whether motorized or non-motorized, poses difficulties that place considerable hardship on the urban poor (The OPEC Fund for International Development Homepage). Rapid increases in car ownership coupled with poor land use planning, inadequate road space, lack of regulated parking systems, uneducated use of the road by pedestrians, and bad driving behavior of motorists have also combined to produce serious congestion, especially in Accra (Abane 1993). Sprawl is evident in several parts of the expanding Accra metropolitan area. As shown in Table 22, the total emissions of carbon monoxide, nitrogen oxides, non-methane VOCs, and sulfur dioxide increased at relatively high rates from 1990 to 1995, and are expected to be on the rise owing to continuing growth in the Accra metropolitan area.

Table 22 Air Pollution Trends, Ghana, 1990-1995

(Unit: Thousand metric tons)	1990	1995
CO	2227.1	2319.7
NOx	105.9	112.9
Non methane VOC	204.2	218.7
SO_2	29.7	32.4

3.1.4.5. Land Use/Transportation Decision Making

The Ministry of Roads and Transport is responsible for the development and maintenance of transportation infrastructure and the provision of transportation services for all modes of transportation in Ghana. The Ghana Roads Sector Development Program (GRSDP) aims at achieving sustainable improvement in the supply and performance of roads as well as road transportation services in a regionally equitable manner. The goal is to increase Ghana's competitiveness in foreign trade and promote linkages in domestic markets which are crucial for rapid and sustained growth (The World Bank Group Homepage). Ghana has undertaken three transportation projects that have contributed to the success of the country's Economic Recovery Program (ERP). The projects, implemented from 1987 to 1998, rehabilitated economically important roads and instituted maintenance programs to prevent road deterioration (Graduate School of Architecture and Preservation Homepage). There is however the need to integrate land use and transportation decisions better to gain better control over congestion, sprawl and the associated air quality problems in the Accra Metropolitan Area. Vision 2020 is Ghana's road map to achieving middle-income country status by the year 2020. The basic objectives of Vision 2020 are to reduce poverty, increase employment opportunities and average incomes, and reduce inequities in order to improve the general welfare and the material well-being of all Ghanaians. In the Vision 2020 framework, the fundamental policy objective of the transportation sector is to establish an efficient, modally complementary and integrated transportation network for the movement of people and goods at the least possible cost within the country. This policy is meant to support Ghana's Gateway Program, a program intended to attract foreign investment and establish Accra as West Africa’s regional distribution and transshipment center (The Official Ghana Education Homepage).

3.2. Synthesis of Findings

A summary of key transportation and sustainability issues for Georgia, South Korea, Colombia, and Ghana is shown in Table 23, and potential areas for improving transportation sustainability for the four cases are presented in Table 24. The cases point to some of the similarities and differences in transportation sustainability issues in countries at different levels of socioeconomic development. The sections below draw out some of these similarities and differences.

All the four areas studied were characterized by rapid population growth in their major metropolitan areas, resulting largely from rapid urbanization (in the developing countries) or population influxes from other urban and non-urban areas, or other countries, to metropolitan areas with booming economies (in the developed countries).

All four cases were also characterized by rapid growth in the demand for vehicular travel and the actual vehicle kilometers traveled (VKT). Thus, congestion, with its debilitating effects, was shown to be a problem independent of the socioeconomic status of the areas studied; however, it was also a sign of booming economies in the metropolitan areas of the higher-GNI countries (Atlanta, Seoul). The higher-GNI areas had begun to address congestion using intelligent transportation systems (ITS) (Atlanta, Seoul) and by shifting from supply-oriented to demand management policies (Seoul). Air quality, like congestion, was a major issue independent of socioeconomic status. While regulatory standards for managing air quality were found in the developed countries, no standards were found for the developing countries. In addition to the debilitating effects of congestion, the lower-GNI countries faced problems with poor and inadequate physical infrastructure, and the need for infrastructure expansion and maintenance were also considered to be important issues in South Korea.

Safety was a major issue in all the four cases. Roadway crashes were found to be a major cause of death in South Korea, Colombia, and Ghana. The cases indicated that roadway safety issues tended to be automobile-centered in developed countries and pedestrian-centered in developing countries. In addition, while crash fatalities were decreasing in Georgia and South Korea, they were increasing in Colombia and Ghana. The developing countries also seemed to have some issues with law enforcement exacerbating their safety problems. The lack of emergency medical services in Ghana also compounded the country's safety problem. The fact that safety is a priority for all countries, independent of economic status, levels and trends in highway crash fatalities, indicates that safety standards are likely to vary widely in the quest for sustainable transportation depending on the present status of transportation safety in a particular country or state. A significant part of the causes of crashes was found to be behavior-related, e.g., bad driving habits, poor vehicle maintenance, lack of appropriate laws, and inadequate law enforcement. The fact that roadway crashes were considered to be a major cause of death in three out of the four areas studied, and the trend in roadway fatalities was on the rise in the two developing countries studied, is an indication that roadway safety is or ought to be a priority in initiatives to address transportation sustainability.

Table 23 Summary of Key Transportation and Sustainability Issues: Georgia (U.S.), South Korea, Colombia, and Ghana

System Attributes Case	Effectiveness/ Efficiency	Safety	Economic	Social and Equity	Environmental	Decision Making	Other Related Issues
Georgia, U.S.	Severe traffic congestion in metropolitan Atlanta Demand management through ITS technologies, HOV lanes, public education initiatives to promote carpooling, telecommuting etc.	Downward trend for fatality and injury crashes Highest fatalities occur on rural two-lane roads	High-income status Commercial transportation positively impacts agricultural industry	High fatality rates on rural two-lane highways	Poor air quality in metropolitan Atlanta with associated respiratory health effects	No formal mandate found for integrated land use/ transportation decision making; however efforts are been made to coordinate the planning activities of land use and transportation agencies	Sprawl and its impact on poor air quality Opportunities for integrating land use and transportation planning better in metro Atlanta
South Korea	Severe traffic congestion Seoul Demand management through: ITS technologies, congestion pricing, traffic impact taxation; higher parking fees in congested areas; exclusive bus lanes	Downward trend for fatality and injury crashes Road traffic fatalities leading cause of death for people under 20 (2003)	High-income status Remarkable growth in GNI over the past 30 years is positively associated with transportation developments made over the past decades	Inter-regional disparities in accessibility and mobility	Air pollution in Seoul: increasing trends in particulate matter and nitrogen dioxide emissions Noise pollution in Seoul	No formal mandate found for integrated land use/ transportation decision making; however there has been the development of National Comprehensive Plan including land use and transportation elements	Disorderly development resulting in environmental damage
Colombia	Bogotá, capital city is highly congested Bus is the predominant mode of transportation, and taxis provide most reliable service in cities Train service undependable Transmilenio Busway project implemented to transform car-centered Bogotá to pedestrian-centered city Poor infrastructure conditions	Upward trend in highway crash fatalities Road traffic fatalities second leading cause of death next to homicides: one traffic crash occurs every 10 minutes Urban pedestrian fatalities constitute highest category of traffic fatalities	Middle-Income Status High poverty rate is positively associated with poor infrastructure conditions High rate of urban pedestrian deaths	High rate of urban pedestrian deaths	Increasing trends in nitrogen oxides and sulfur dioxide emissions	No formal mandate found for integrated land use/ transportation decision making; however Ministry of Transportation is involving several relevant agencies in its decision making	High level of poverty Rapid Urbanization Poor enforcement of traffic laws Public security issues Extreme inequality in income distribution Leading exports facing uncertain future

Table 23 continued

System Attributes Case	Effectiveness/ Efficiency	Safety	Economic	Social and Equity	Environmental	Decision Making	Other Related Issues
Ghana	Severe congestion in Accra metropolitan area Lack of effective public transportation system Poor infrastructure	Upward trend in highway crash fatalities Road crashes are a leading cause of death in the country; the majority of which occur on roads in rural areas Pedestrian deaths constitute the largest category of road traffic deaths followed by buses and minibuses	Low-income status Significant percentage of agricultural exportable produce decay due to poor road access: disincentive for farmers to produce	Wide disparities in road access and infrastructure condition in urban and rural areas	Rapidly increasing trends in carbon dioxide, nitrogen oxides and non-methane VOCs in Accra	No formal mandate found for integrated land use/ transportation planning	High level of poverty Poor infrastructure conditions Poor law enforcement Lack of emergency medical services Poor land use planning in metropolitan areas

Table 24 Examples of Potential Areas for Transportation Sustainability Improvements: Georgia (U.S.), South Korea, Colombia, and Ghana

	Georgia, U.S.	South Korea	Colombia	Ghana
Potential Areas for Transportation Sustainability Improvements	Implement more effective and efficient public transportation systems Decrease automobile demand by more actively promoting carpooling, telecommuting, etc. Improve safety measures especially on rural two-lane roads Integrate land use and transportation planning better in metro Atlanta	Improve road safety by effectively ordering the road and changing driver behavior Focus more on effective congestion management, e.g., immediate incident management Minimize inter-regional disparities in accessibility and mobility Implement more advanced environmental policy pertaining to air and noise pollution Integrate land use and transportation planning more effectively	Improve pedestrian safety especially in urban areas Improve law enforcement Implement more reliable public transportation systems Improve infrastructure condition Enforce traffic and environmental laws more adequately	Improve roadway and pedestrian safety Improve emergency medical services Improve law enforcement Implement effective public transportation system Improve road accessibility especially for agricultural incentives Improve infrastructure condition particularly in rural areas Improve land use planning in metropolitan areas

The opposite trends in highway crash fatalities in the developing and developed economies, and the different levels of activity relative to regulating air quality indicate that while across-the-board standards may be necessary to promote movement toward transportation system sustainability in the international community, it may also be difficult to gain consensus for such standards on various important issues given the wide variation in the present status and trends for various transportation sustainability indicators. The fact that crash rates were generally caused or exacerbated by the behaviors of system users indicates that measures for changing behaviors also ought to play an increasingly important role in improving the safety of highway systems around the world. Korea's recent successes with using behavioral-related policies to reverse the trends in highway fatality crashes point to the potential effectiveness of coupling behavior-related policies with infrastructure, operational and information technology improvements, as well as other measures to address transportation system safety.

In all the cases, equitable access to adequate transportation was considered an issue as social equity is one of the most important elements in moving toward sustainability. It is important that sustainability indicators explicitly capture equity given that several economic indicators (e.g., GDP) reflect only the "average" of conditions but not the variance or discrepancies among populations. It is possible for example that continuing economic development in various countries may tend to increase the gap between higher-income and lower-income populations, which would not be captured by the use of average indicators. Equity-related indicators such as access to basic social and economic services for those without cars, affordability of public transit services especially for lower income groups, and the quality of transit with respect to the mobility impaired, can capture social equity across different income levels, age, and other demographic categories. Equity issues have arisen along the lines of socioeconomic class (Georgia, South Korea, and Ghana), race (Georgia), or urban/rural status (Georgia, Colombia, and Ghana). Georgia's fatalities on rural two-lane roads have been significantly higher than fatalities in all other categories. In South Korea, regional disparities were found relative to access to transportation and other socioeconomic resources. Both Colombia and Ghana have experienced relatively high pedestrian fatality rates. In Colombia, Bogotá, Medellin, and Cali (major cities) have experienced high pedestrian fatality rates. In Ghana, pedestrian deaths constituted the largest category of fatalities among all road users, followed by occupants of buses and minibuses; and the majority of road traffic fatalities and injuries occurred on roads in rural areas.

While no mandates were found for integrated land use and transportation planning in all the cases, Georgia was making some efforts toward integrating land use and transportation planning, South Korea had developed a comprehensive land use/transportation plan, and Colombia's Ministry of Transportation had taken the initiative to work with other agencies, including agencies with control over land use decisions, in order to make more effective decisions.

While several data were found on the physical extent of transportation infrastructure assets in all cases, little was found to indicate how effectively and efficiently the existing transportation system was serving the country or state's residents by providing them with access to their basic needs. Such measures would strengthen our understanding of the overall effectiveness of the transportation/land use system.

South Korea's remarkable transition from low-income to high income-status in the past three decades offers an excellent example for low-income economies that such transitions are feasible and involve significant and sustained investments in infrastructure and information technology, as well as the political will to implement behavioral-related policies that improve the quality of the transportation environment. It also indicates that the drivers for congestion and associated air quality issues in metropolitan areas (e.g., high population growth rates, rapid urbanization, and pressures to relocate to areas with booming economies) do not automatically disappear with successful economic growth, and must be proactively managed simultaneously as economic growth is pursued, in order to preserve regional quality-of-life gains. South Korea has also responded to the world's emerging movement toward achieving sustainability by inaugurating its own Presidential Commission on Sustainable Development (PCSD) in 2000 followed by corresponding legislations.

Colombia's example with the Transmilenio Project in Bogotá is demonstrating the feasibility of transforming a city from an auto-centered to a pedestrian-oriented city and the importance of effective public transportation systems for addressing some of the congestion and air quality problems in metropolitan areas, particularly in areas with adequate population densities to support effective public transportation. As rapid urbanization occurs in developing countries, and rapid metropolitan population growth continues to occur in developed economies, both of which continue to create increased population densities to support public transportation, the development of effective public transportation (less developed economies) and improvement of the convenience of existing public transportation systems (more developed economies) grow to be more feasible options for transforming neighborhoods from auto-centered to public transportation-centered systems.

All four cases indicate that there is a serious need to consider taking formal steps to integrate the transportation and land decision making processes better, in order to address more effectively such issues as sprawl (Atlanta, Accra), disorderly development (Seoul), and the effective organization of highly populated urban areas (Bogotá). Rapid population growth in the Atlanta and Seoul Metropolitan Areas, and rapid urbanization in Bogotá and Accra, as well as the increasing rate of vehicle ownership in these areas, all point to an urgent need for institutions or institutional mechanisms that are better equipped to plan more comprehensively including using land use controls to gain a better handle on a broader range of influences on metropolitan quality of life.

3.3. Policy Implications

The findings of this case study have important implications for the development of priorities and standards for progress toward achieving transportation sustainability within the international community. First, the data available on different aspects of transportation systems varies widely in its adequacy and completeness. No data was found for any of the cases capturing the relative levels of accessibility that the population had to basic services and amenities, indicating that it would be difficult to measure gains in accessibility that occur without improvements in mobility, which is a major area of opportunity for progress toward sustainability. The data on the adequacy of the transportation system was largely mobility-focused. In addition, metrics for data on particular attributes, e.g., safety, were different for the different cases. For example, while crash fatalities were being measured as a function of vehicle kilometers traveled in

Georgia they were being measured as a function of the number of vehicles in the South Korea, in Ghana as the total number of injuries or fatalities per a standard number of people, and in Colombia by the total number of fatalities or injuries per year. Thus, safety gains or losses would be more difficult to capture using the data of the low/medium-income countries. Data standards to facilitate comparability would support progress toward sustainability.

The widely different socioeconomic conditions represented by the four case studies indicate why it would be difficult to develop uniform standards for attaining sustainability within the international community and seem to suggest that “movement toward sustainability” may be a more realistic objective than “achieving sustainability.” In practice therefore, the fact that there are few widely accepted standards for what would constitute sustainability should not be a major obstacle for entities interested in taking steps to move toward sustainability because different policy, plan, program, and project actions can be classified objectively as sustainability gains or losses along the lines of the commonly accepted criteria for sustainability (e.g., effective/efficient/safe access, economic growth, environmental, and social equity, for transportation). At the same time, the commitment of various entities (local jurisdictions, states, countries, nations, and the global community) to sustainability is partially dependent on the commitment of their neighboring entities to move toward sustainability, because of the existing threat of “Tragedy of the Commons” inclinations.

First, this would seem to suggest that certain groupings of entities may provide better forums for achieving consensus on standards to move toward sustainability: entities that have similar socioeconomic conditions and thus share feasible goals, priorities, and constraints. For example, while stabilizing or reversing the trends in roadway fatalities may be plausible interim targets for Colombia and Ghana, such targets are not relevant for South Korea and Georgia, and thus lumping these four entities together in the development of safety standards for sustainability may not be a very worthwhile endeavor. Success in building consensus for standards would entail a convergence of minds, which may more likely occur among entities that have similar issues to contend with. Second, it would also seem to suggest that, for practical purposes, standards may be movable targets with associated time frames rather than fixed endpoints anchored at some infinite points in time. A plausible objective may be to move "regions of similar status and constraints" toward sustainability through consensus-based interim targets that are subject to change over time. The term region is used in this context to capture entities with similar existing socioeconomic conditions with respect to achieving sustainability in a particular domain, e.g. transportation. Thus, such regions may be geographically contiguous but not necessarily so. For example, entities with vehicle fatalities on the rise are natural members of a region that would be interested in reversing trends in roadway fatalities. Thus, the levels of comparability among a particular group of entities would have a direct impact on their ability to reach consensus on particular targets for sustainability in agreed-upon time frames.

These ideas suggest potential differences in the types of forums that could be successfully adopted to develop *intra-regional standards* in contradistinction with *inter-regional standards*. It would seem that the successful development of intra-regional standards (interim targets) would need to be more sensitive to the needs of members of a particular region. Inter-regional agreements, on the other hand, could be negotiated among regional representatives on issues or "bundles of issues" that are not necessarily similar but offer opportunities for give-and-take, taking into consideration the different needs and interim goals of the participating regions. Under such a framework, standards that cut across regions would not necessarily be *similar* for all regional entities involved, but rather *acceptable* based on a mindset of tradeoffs brought to the negotiation table and an understanding that the prevailing conditions in different regions can be significantly different.

One may also argue that some sustainability issues have farther-reaching influence than others, and that in developing standards, the former would be more important across regions than within regions. For example, vehicle emissions may be considered farther-reaching than crash fatalities in the quest for acceptable across-the-board standards, because the impacts of the former on neighboring entities are potentially more significant than the latter. Distinguishing among indicators that have intra-regional versus inter-regional implications could be helpful for understanding how much of a driver regional commonalities would be in the successful development of standards for sustainability, and thus for crafting issues or "bundles of issues" that are more likely to gain consensus at appropriate levels (local, national, regional, global) of decision making, while temporarily managing at more disaggregate levels issues that are less likely to gain across-the-board consensus.

These ideas are intended to offer food for thought to the broader community interested in finding more successful models to develop standards for promoting movement toward sustainability in the international community. Perhaps different regionally-based standards that are perceived as equitable across regions stand more of a chance of being adopted than across-the-board standards that may fail to acknowledge the needs and constraints of various entities while catering to others (from the very nature of the wide scope of conditions present in different socioeconomic contexts). A model where standards are crafted as movable targets based on mutually agreed upon time frames and where entities' memberships in regions can change, depending on the changes in their sustainability status, may offer more appropriate incentives for accelerated movement toward sustainability among a broader scope of entities with widely different socioeconomic conditions and constraints.

Several issues worth considering remain important subject material to advance progress toward sustainability. Particularly important are the effects of population densities on achieving and measuring transportation sustainability (in particular, megacities such as Seoul, Los Angeles, and Lagos may offer a unique set of challenges for the development of sustainable transportation systems); understanding causes and drivers of sustainability and non-sustainability in transportation systems, understanding the relationships between implemented economic/infrastructure policies and the resulting system outcomes (e.g., safety, congestion, air quality); and appropriate indicator sets for measuring progress toward sustainability at various levels of socioeconomic development.

For the purposes of developing sustainability evaluation procedures, perhaps the most important messages from this study are that different metropolitan regions may have different sustainable development priorities. Thus, it would be critical to determine the model parameters based on the priorities (usually captured in regional planning goals and objectives) for sustainable development of the region. In addition, what this study implies is that just as the development priorities for different regions may change (spatially speaking), the development priorities for a particular region may evolve as a function of time as its needs change. Hence, it is to be expected that sustainable development priorities for a particular region may evolve over time. Thus, for sustainability evaluation methods to remain relevant to the particular priorities of a region, these methods would have to be versatile enough to address changing priorities as a function of time.

CHAPTER 4

DEFINING SUSTAINABILITY

While the word “sustainability” is becoming more prevalent throughout various disciplines, the definition of sustainability is still considered to be controversial. The main reason is that different people may define sustainability with different emphasis on the different dimensions of sustainability based on their interests and critical issues. Sustainability may be considered at multiple levels of political decision making. For example, we may consider sustainability at a regional or global level. As previously stated, this study mainly focuses on the evaluation of transportation and land use plans that affect regional sustainability. The objective of this chapter is threefold. First, it is to contemplate what constitutes transportation system sustainability and what the interactions among these elements affecting sustainability are. Second, it is also to discuss the interactions between the defined dimensions of sustainability and the outer policy or institutional sphere that includes various urban or metropolitan issues beyond transportation systems. Finally, it is to discuss how one would compare the extent to which plan alternatives from different metropolitan areas affect progress toward sustainability where a wide range of sustainability issues exist.

4.1. Elements of Transportation System Sustainability

Based on the findings from the literature review and the case studies, transportation system sustainability should at the very least incorporate attributes of system effectiveness and system impacts on economic development, environmental integrity, and the social quality of life. Thus, the four essential dimensions of transportation system sustainability could be considered to be system effectiveness, economic sustainability, environmental sustainability, and social sustainability. Necessary factors of transportation system effectiveness include system performance for multimodal transportation systems such as regional highways and public transit systems. Necessary environmental factors for sustainability include resource preservation (such as fossil fuels and land), air and noise pollution prevention, and greenhouse effect prevention for broader sustainability issues associated with the livability of current and future generations. Necessary economic factors for sustainability include economic efficiency, financial affordability, and regional economic development through improved accessibility. Necessary social factors for sustainability include social equity related to income and minority groups, public health, safety and security, accessibility to various services, and all these four factors inevitably affect overall quality of life.

This section further examines possible performance measures that monitor progress toward or away from sustainability and how these entities influence each other. To identify and display defined elements and their interactions more effectively, an influence diagram is employed for each dimension of sustainability. An influence diagram is a simple graphical representation of a decision situation where different decision elements such as decisions, uncertainties, and consequences are displayed as different shapes. These shapes are linked with arrows in specific ways to show the relationships and relevance among the elements. Rectangles represent decisions, ovals represent chance events, and rectangles with rounded corner represent consequences (Clemen, 1996). A decision is a variable that decision makers have the power to control, a chance variable captures uncertainty which will be resolved before the payoff and decision makers cannot control it directly, and a consequence variable is a value determined by the quantities it depends on. An objective variable, represented by hexagons, is a value or a payoff which generally is a quantitative value that decision makers attempt to maximize or minimize (Clemen, 1996). Figures 8 through 11 illustrate examples of influence diagrams showing the relationships among essential elements of transportation system sustainability.

4.1.1. System Effectiveness Dimension of Sustainability

Figure 8 illustrates a possible representation of the effectiveness dimension for transportation system sustainability using an influence diagram. Common goals and objectives of transportation system effectiveness are often related to improving system performance of regional highways and public transit systems (shown as a hexagon). Measures of transportation system performance may include vehicle miles traveled, travel speed, congestion, or delay, travel times, throughput, or other parameters (FHWA, 2004). Transportation and land use decisions (the rectangle) will influence mode share of private automobiles and public transportation systems which is the only uncertain variable (the circle) in the diagram. A new modal spilt will affect vehicle miles traveled, such as total vehicle miles traveled per capita, transit passenger miles traveled, and freight ton-miles, and vehicle miles traveled in turn affects traffic congestion evidenced by average freeway and arterial speed that are often used as surrogate measures to capture the level of mobility and reliability. Even though average freeway speed is often used as a proxy for freeway congestion, it may not fully represent the level of mobility because different regions have different freeway configurations and origin-destination (O-D) pairs served by freeways. Transportation network of some regions may be heavily focused on arterial systems, and most of O-D trips are served by arterial roads while freeways rarely have traffic congestion.

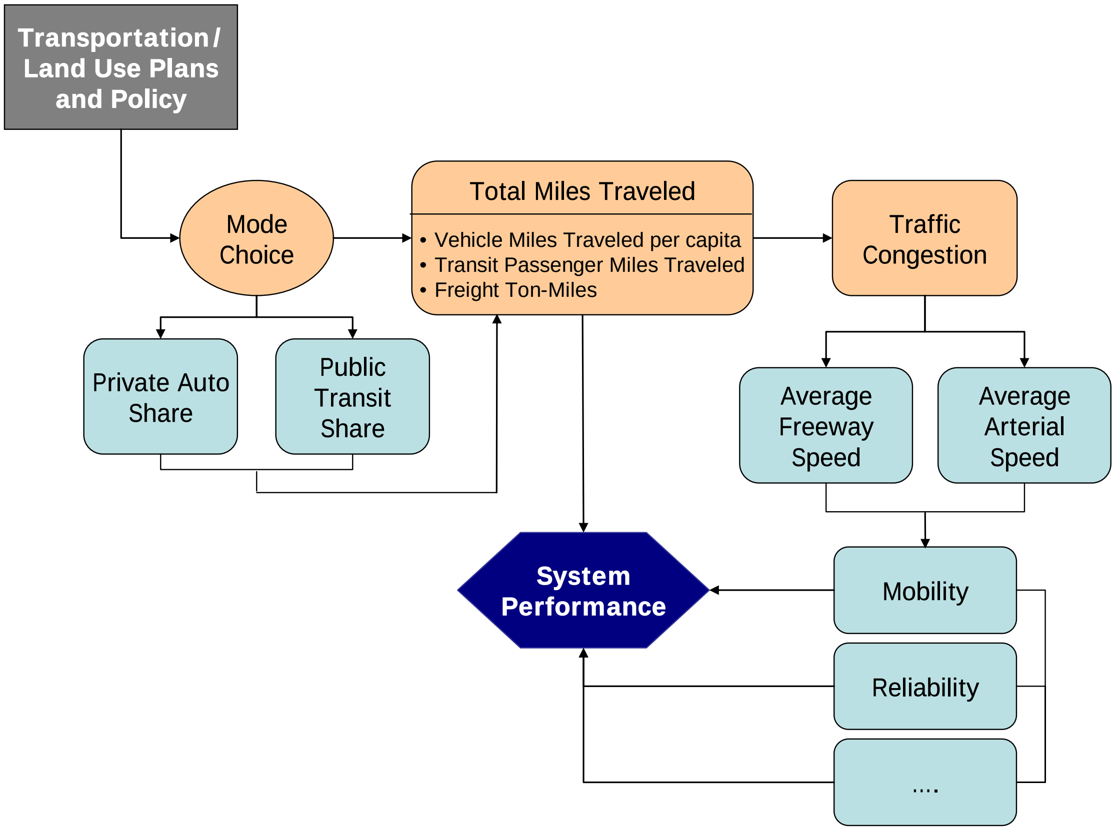

Figure 8 Effectiveness Factors for Transportation System Sustainability

There may be some different point of views with respect to the desirable direction of certain performance measures. Total vehicle miles traveled per capita, for example, evaluates the average distance each person in the region drives each day. Generally, the smaller the vehicle miles traveled per person, the more effective transportation system assuming that travelers are able to minimize their trips while meeting their personal needs. A high number of vehicle miles traveled per person, however, may indicate that travelers are accommodating their diverse desires (such as leisure trips or driving as a pleasure) while consuming unnecessary fossil fuels. Similarly, transportation system performance is generally considered to be better off when average freeway speed is higher. It should also be noted that higher freeway speeds may result in more usage of private automobiles thus decreasing the extra benefits of using transit systems which are far more sustainable transportation systems than automobiles. These different viewpoints are food for thought from a sustainability-oriented standpoint in the sense that decision makers should not look at performance measures in isolation but they should consider them collectively to obtain better indication of movement toward or away from sustainability.

4.1.2. Economic Dimension of Sustainability

Figure 9 depicts a possible representation of the economic dimension for transportation system sustainability using an influence diagram. Common goals and objectives of economic dimension include maximizing economic efficiency, maximizing financial affordability, and promoting regional economic development (shown as three hexagons). Economic efficiency can be defined as the largest excess of social benefits over social costs among the possible alternative programs or policies (Web definition: Economic efficiency). Regional economic development can be defined as the expansion of a community's property and sales tax base or the expansion of the number of jobs through office, retail, and industrial development (Web definition: Economic development). In general, a transportation and land use decision (the rectangle) will improve regional accessibility to some extent, which results in changes in the mode share of private automobiles and public transportation systems. A new modal spilt will affect total vehicle miles traveled, and travel cost will depend on the mode that travelers use and how much they travel. Total vehicle miles traveled influences traffic congestion, and the level of congestion in turn affects total time spent in traffic as well as user welfare benefits resulting from less time travelers spent in traffic. Affordability and user welfare influence economic efficiency while improved accessibility and user welfare affect regional economic development.

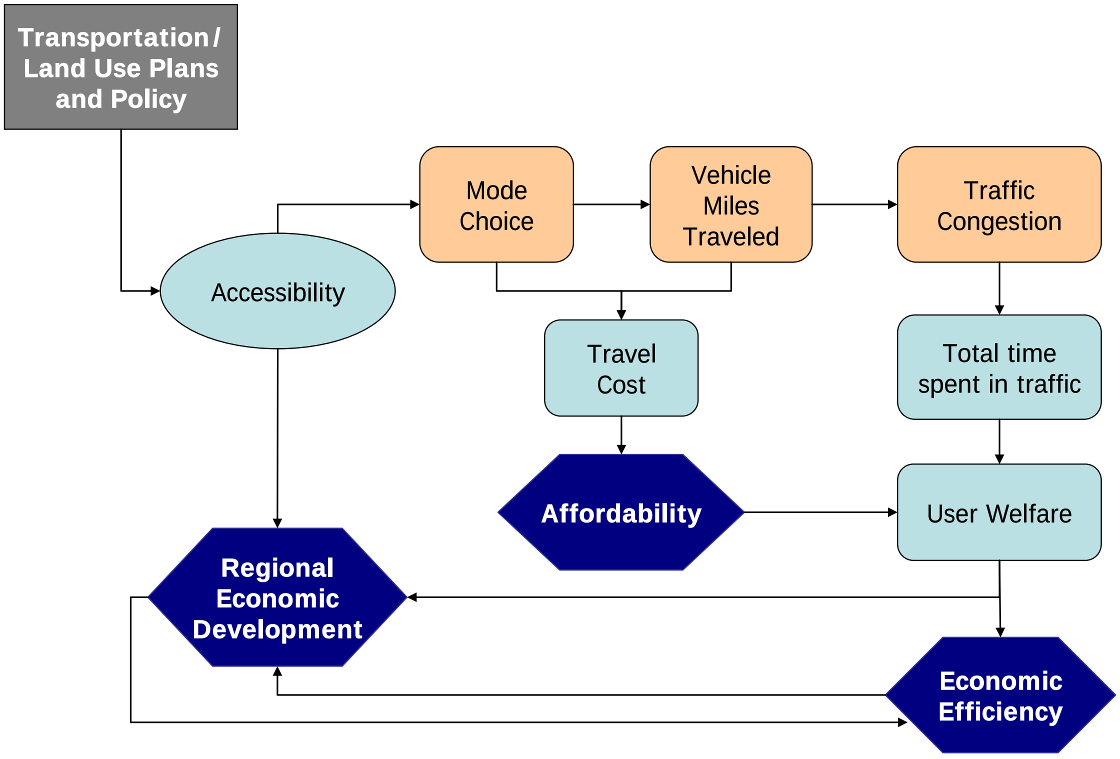

Figure 9 Economic Factors for Transportation System Sustainability

4.1.3. Environmental Dimension of Sustainability

Figure 10 is an influence diagram depicting a possible representation of the environmental dimension for transportation system sustainability. Common goals and objectives of environmental dimension include minimizing greenhouse gas emissions, minimizing air pollution, minimizing noise levels, and minimizing resource use (shown as three hexagons). Transportation and land use decisions (the rectangle) influence mode share of private automobiles and public transportation systems as well as land consumption by transportation infrastructure. Resulting VMT and traffic congestion influence various environmental factors such as fuel consumption, CO_2 emissions, CO, VOC, and NO_x emissions, and traffic noise levels. Land and fuel consumption affect resource use, CO_2 and Ozone emissions influence global climate change, and other emissions affect air pollution and noise levels.

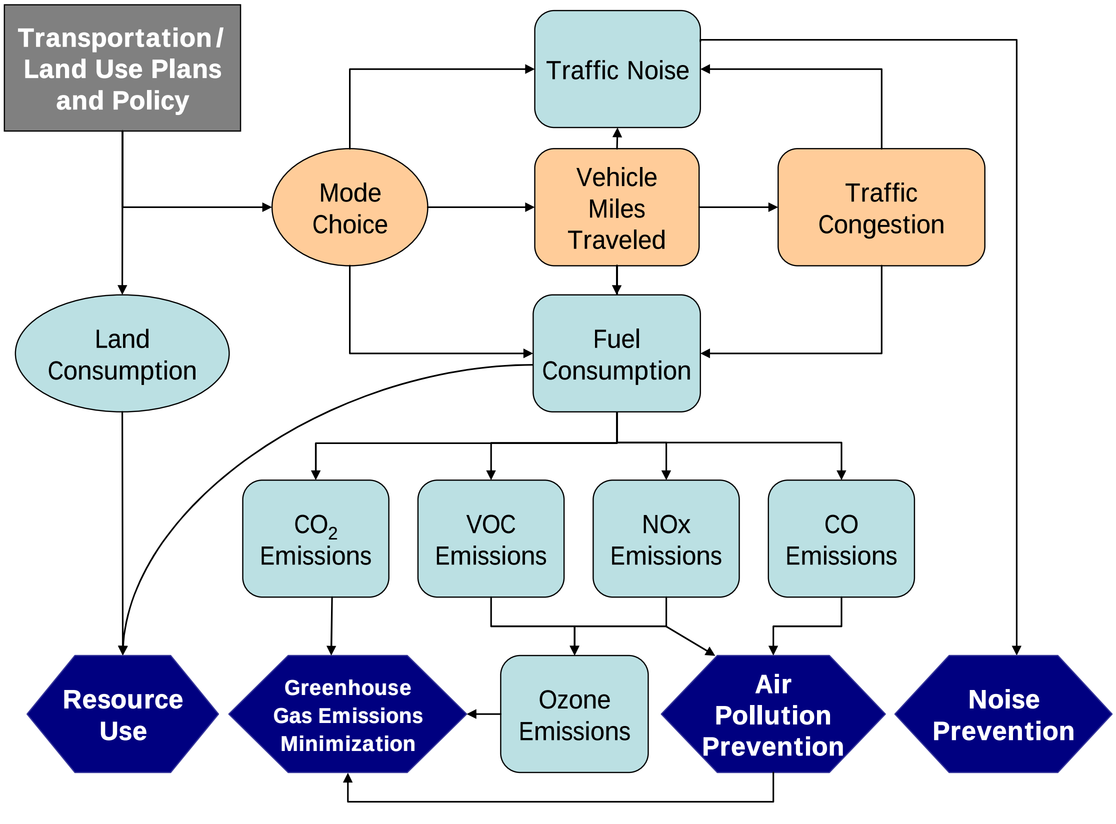

Figure 10 Environmental Factors for Transportation System Sustainability

4.1.4. Social Dimension of Sustainability

Figure 11 illustrates a possible representation of the social dimension for transportation system sustainability using an influence diagram. Common goals and objectives of social dimension include maximizing social equity, improving public health, increasing safety and security, increasing accessibility to various services, and improving overall quality of life (shown as hexagons).

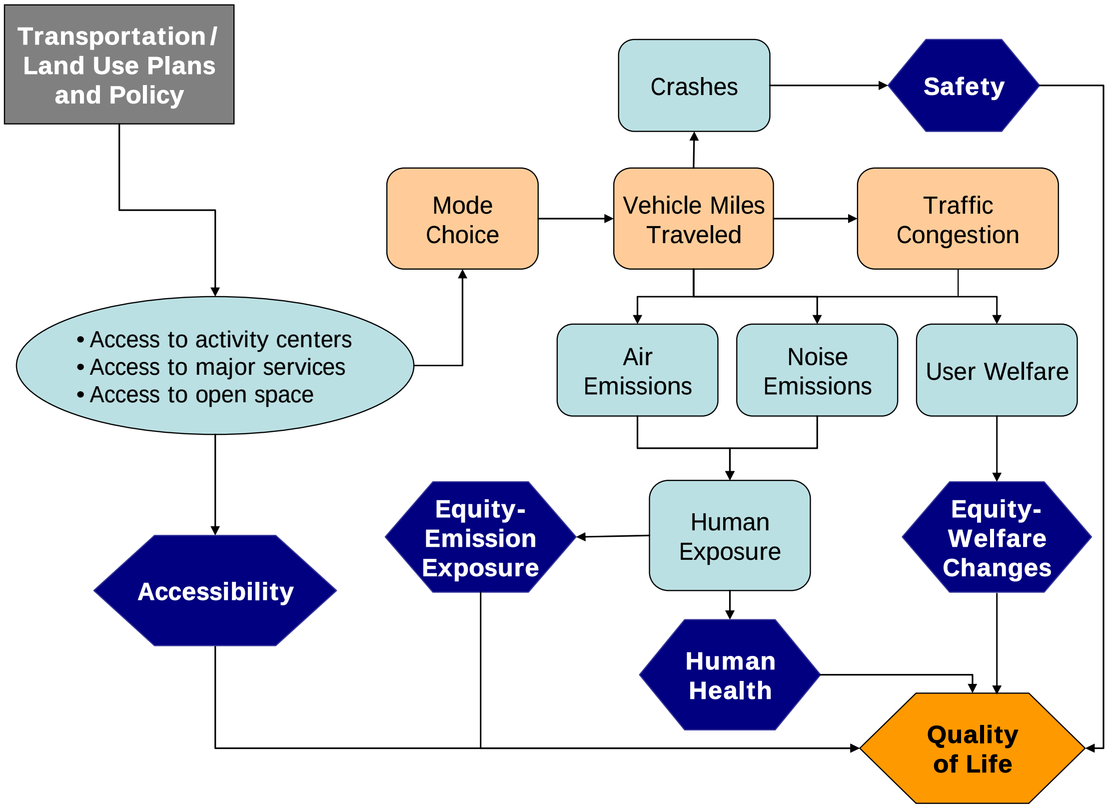

Figure 11 Social Factors for Transportation System Sustainability

Transportation and land use decisions (the rectangle) improve regional accessibility to various services to some extent, resulting in changes in the mode share of private automobiles and public transportation systems. A new mode split influences total VMT, and the number of crashes is correlated with total VMT. Total VMT and resulting traffic congestion have an environmental (air and noise emissions) and economic (user welfare) impact on sustainability. Air and noise emissions influence the extent of human exposure to such pollution, and human exposure affects the equity of emission exposure as well as public health. The equity of welfare changes depends on the improved user welfare derived from travel time and cost savings. Social equity, public health, safety and security, and accessibility all contribute to the quality of life.

4.1.5. Synthesis

This section discusses a controversial and evolving issue on what constitutes transportation system sustainability. The four essential dimensions of sustainability could be considered to be *transportation systems effectiveness*, *economic sustainability*, *environmental sustainability*, and *social sustainability*. Necessary factors of transportation system effectiveness include system performance for multimodal transportation systems such as regional highways and transit systems. Necessary environmental factors for sustainability include resource preservation (such as fossil fuels and land), air pollution prevention, noise prevention, and greenhouse gas emissions minimization for global sustainability issues associated with the livability of current and future generations. Necessary economic factors for sustainability include economic efficiency, financial affordability, and regional economic development by improving accessibility. Essential social factors for sustainability include social equity issues related to income and minority groups, public health, safety and security, accessibility to various services, and all four factors inevitably affect overall quality of life.

Although the proposed essential elements and their relationships are by no means exhaustive, these elements should be considered in most situations when transportation system sustainability is addressed. In general, a transportation and land use decision sequentially influences mode choice, VMT, and traffic congestion. The uncertain effects of these variables will subsequently affect system effectiveness, as well as the economic, environmental, and social dimensions of sustainability. The influence diagrams help to capture some of the key interactions among these elements. These diagrams should at the very least serve as an overview guide for decision makers who attempt to incorporate sustainability considerations into transportation planning and understand key factors of sustainability and their relationships. However, it may be appropriate that decision makers include additional measures specialized to address particular sustainability needs or objectives in their local context.

4.2. Transportation System Sustainability in the Policy Making Context

As discussed earlier, system effectiveness, environmental, economic, and social dimensions can be considered essential dimensions of sustainability. This section identifies interactions between these dimensions of sustainability and the outer policy or institutional sphere that includes various urban or metropolitan issues beyond transportation systems.

Figure 12 conceptualizes the relationship among the four sustainability dimensions as well as the interaction among these dimensions and the outer policy sphere. These sustainability dimensions are considered to be connected by their common elements or drivers which simultaneously influence multiple sustainability dimensions. Meanwhile, these dimensions also interact with the outer policy or institutional sphere. The outer policy sphere includes various urban or metropolitan issues not under the direct control of transportation officials, e.g., population/employment growth, market forces, and other government policies. Transportation systems are influenced by and influence the outer organizational and institutional network of policymakers, firms, non-governmental organizations, and stakeholders that together comprise the broad policy system that acts upon the sustainability dimensions (Dodder et al., 2004).

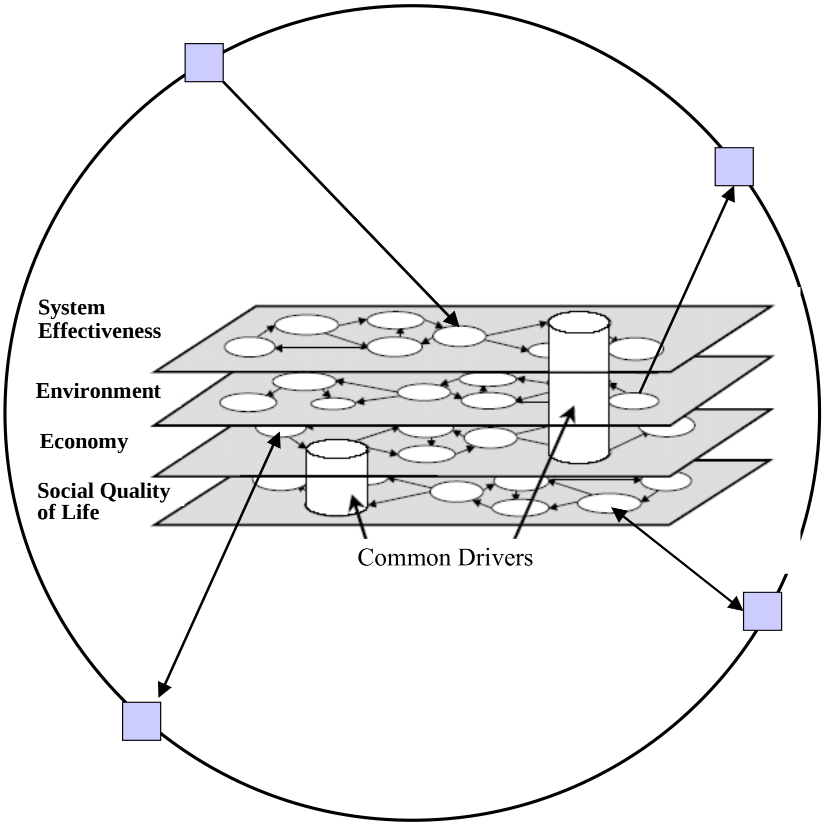

Figure 12 Interaction between sustainability dimensions and the outer sphere [Adapted from Dodder et al., 2004].

The conceptual representation of interactions between sustainability dimensions and the outer sphere can be used as an effective analogy to transportation system sustainability in the policy making context. Figure 13 illustrates a particular hierarchical relationship among the four sustainability dimensions and possible outer policy variables that interact with transportation system sustainability. First of all, a transportation and land use decision sequentially influences mode choice, vehicle miles traveled, and traffic congestion. The uncertain effects of these variables affect transportation system effectiveness by improving mobility and reliability, for example. A decision and the resulting system effectiveness will consequently influence the environmental factors of sustainability: land and fuel consumption, greenhouse gas emissions, and air/noise pollution. At the same time, a decision and the resulting system effectiveness will also affect the economic factors of sustainability: improved accessibility, travel cost, total time spent in traffic, and user welfare. Finally, a decision and the resulting system effectiveness, environmental, and economic level of sustainability will subsequently affect the social factors of sustainability: accessibility, equity of emission exposure and welfare changes, safety, human health, and overall quality of life.

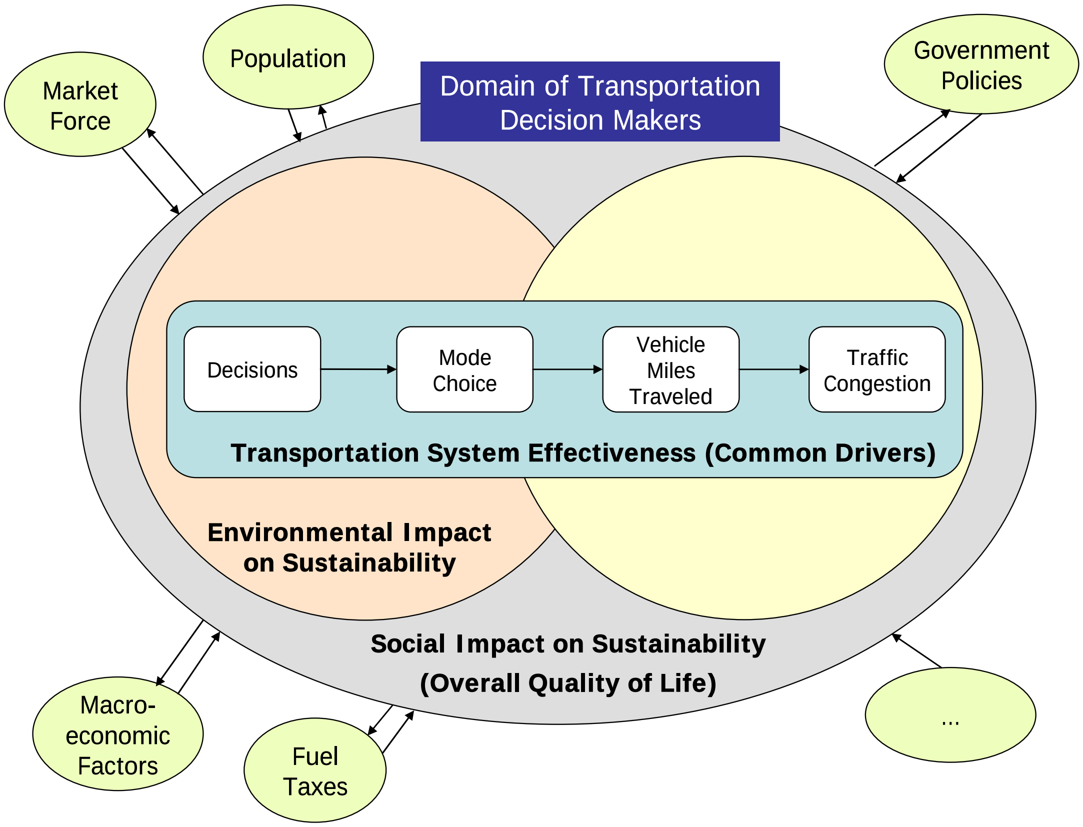

Figure 13 Transportation System Sustainability in the Policy Making Context

The inside of the social impact sphere may be considered to be a domain of transportation decision makers, and the outer space refers to other elements that influence and are influenced by transportation system sustainability but probably beyond the domain of transportation decision makers. As shown in Figure 13, transportation system sustainability interacts with the outer organizational and institutional sphere which includes various issues beyond the transportation system per se such as market forces, population growth, macroeconomic factors, and various government policies. Therefore, to be effective, sustainability considerations should include not only proposed sustainability dimensions but also outer organizational and institutional network of policymakers, firms, non-governmental organizations, and stakeholders that together comprise the broad policy system that acts upon the sustainability dimensions. In other words, the sustainability of transportation systems can not be fully addressed and evaluated within a domain of transportation decision makers. It is important that decision makers do not consider transportation system sustainability in isolation from related broader issues beyond transportation planning in a region. When considered collectively, the nature of "sustainability" tends to be better understood and the progress in movement toward or away from sustainability can be monitored as a whole.

4.3. Ecological Footprint and Sustainability

Considering that sustainability issues significantly vary over different metropolitan areas, the relative effectiveness of sustainability evaluation is a function of how well it monitors progress toward the particular vision and goals in the regional context and how well it can compare the progress of different regions that have different regional priorities. This section discusses how one would compare the sustainability of plan alternatives from different metropolitan areas where a wide range of sustainability issues exist. A number of efforts around the world have developed measures and indexes that capture a unique perspective of progress toward sustainability. It is necessary to link an emerging measure with these objective sustainability measures in order to track the impacts of alternative plans on some objective scale of sustainability and enable comparison of different regions on the basis of their progress toward sustainability.

One example of existing sustainability measures is the Ecological Footprint defined as “the area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces, wherever on Earth the land and water is located” (Wackernagel and Rees, 1996). The measure essentially compares actual throughput of renewable resources relative to what is annually renewed by accounting for the flows of energy and matter to and from any defined economy and converting these into the corresponding land/water area required for nature to support these flows. The total “footprint” for a designated population’s activities is measured in terms of a global hectare (acre) which is one hectare (2.47 acres) of biologically productive space with an annual productivity equal to the world average (The Sustainable Scale Project Homepage). By comparing such measures over different regions, decision makers can evaluate some objective scale of sustainability resulting from plan alternatives in different metropolitan areas with different regional priorities. Essentially, the Ecological Footprint varies extensively by region over the world as shown in Figure 14. The Ecological Footprint, the average per person resource demand, for the world as a whole is the product of population times per capita consumption and reflects both the level of consumption and the efficiency with which resources are turned into consumption products. Not surprisingly, North America region has the largest Ecological Footprint: 9.4 global hectares per person which is twice of that of European 25 countries (Global Footprint Network Homepage). Besides, most of the amount of North America's Ecological Footprint is essentially originated from the United States not from Canada.

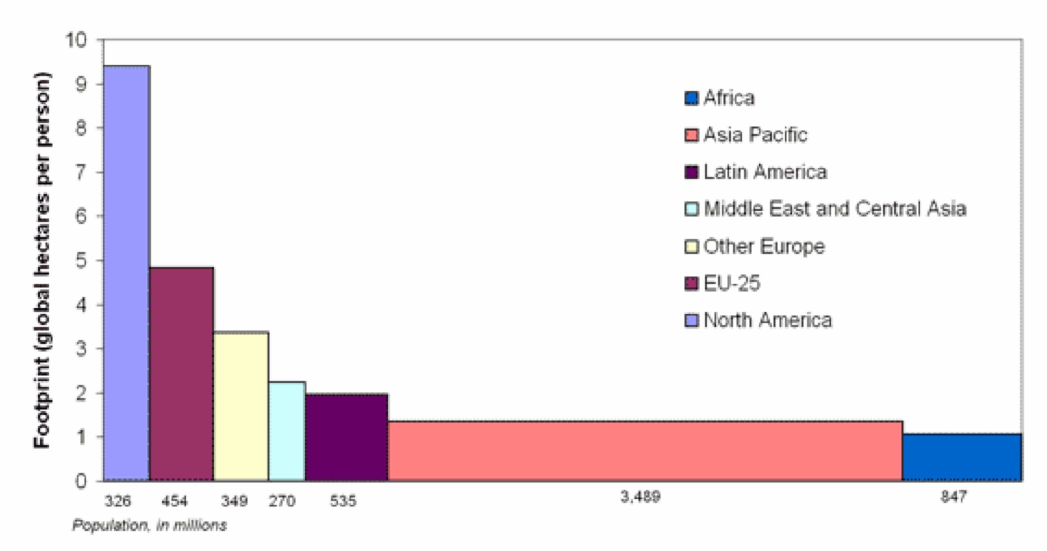

Figure 14 Ecological Footprint by Region (versus Population)
(Source: Global Footprint Network Homepage)

Such measures will help capture a snapshot of sustainability levels throughout different metropolitan regions for a particular moment. Underlying trends over time, however, may provide a more important indication of a region's movement toward or away from sustainability. Figure 15, for example, depicts a trend of the Ecological Footprint (the average per capita resource demand) and Biocapacity (per capita resource supply) in United States over a 43-period. According to the figure, resource demand for the U. S. exceeded resource supply even before 1970s, and the term "ecological overshoot" is used to explain such condition. The Ecological Footprint was 9.6 global hectares per person (2.2 ha/person for the world) in 2003, and the global ecological overshoot was 4.8 global hectares per person (0.5 ha/person for the world). The global ecological deficit has been continuously increasing indicating that the region has moved away from sustainability over a couple of decades from the Ecological Footprint standpoint. Thus, some extent of societal action should be introduced to reverse this unsustainable trend which exacerbates the situation where humanity's ecological resource demands exceed what nature can continually supply.

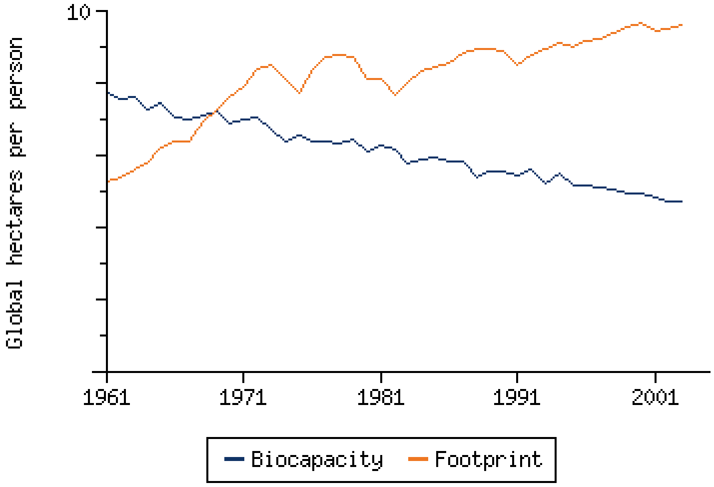

Figure 15 United States of America's Footprint: 1961-2003
(Source: Global Footprint Network Homepage)

The Ecological Footprint can be further investigated by footprint components of cropland, grazing land, fishing ground, forest (timber or fuel wood), carbon, nuclear, and developed land. Figure 16 shows the components of the average per person Ecological Footprint in the U.S. over a 43-year period. More than half of the Ecological Footprint in the U.S. consists of carbon dioxide (CO_2) absorption, and the ratio of CO_2 absorption has been increasing significantly over time (Global Footprint Network Homepage).

The example of the Ecological Footprint measure demonstrates how decision makers can monitor the sustainability of humanity by investigating the spatial and temporal characteristics of selected measures. If one concentrates only on the snapshot (cross-section) of what appears to be related to sustainability, he or she might not notice an important signal/movement toward or away from sustainability. Sustainability, by nature, should not be considered as an outcome resulting from isolated events but as an outcome resulting from long lasting efforts and complicated interactions between related policies. This dissertation mainly focuses on evaluating regional sustainability changes resulting from the selected transportation and land use plans for Atlanta Metropolitan Region for the future: the year 2030. The overall impacts of these two competing future plans on sustainability are compared relative to the impacts of current transportation systems as a baseline of 2005. Resulting sustainability impacts, ranging from system effectiveness, economic, environmental, and social dimensions of sustainability, should provide an indication of whether the Atlanta region is moving toward or away from achieving transportation system sustainability between now and the future. In addition, the research methods can be used in evaluating the sustainability benefits of future plan alternatives, while considering associated tradeoffs among alternatives put forward as well.

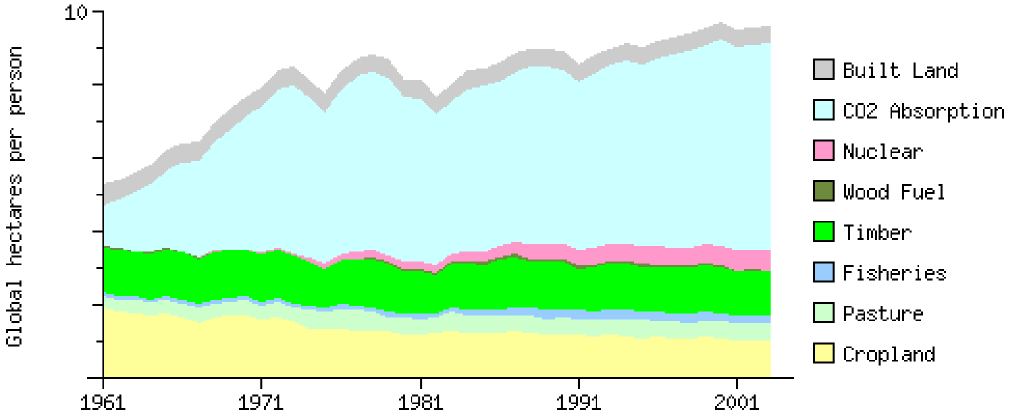

Figure 16 Ecological Footprint by Components in the U.S.
(Source: Global Footprint Network Homepage)

As discussed earlier, this study attempts to track progress toward sustainability not as a snapshot isolated from ever-changing conditions but as a temporal trend. This study introduces the multiple criteria decision making (MCDM) methods in conjunction with a composite sustainability index tool to not only identify superior plan alternatives but also consider tradeoffs among alternatives put forward. Linking these evaluation results with some objective sustainability measures, such as the Ecological Footprint, should help validate the effectiveness of the proposed framework to some extent and enable comparison of different regions on the basis of their progress toward sustainability.

CHAPTER 5

METHODOLOGY AND DATA

As discussed in the Introductory and Literature Review chapters, few metropolitan planning organizations have attempted to incorporate the impact of transportation system and land use changes on sustainable development while simultaneously addressing impacts on the economy, environment, and social equity. The previous chapter depicted sustainable development priorities in different contexts showing that there are no universal drivers and performance measures for transportation system sustainability and that the relative effectiveness of sustainability evaluation is a function of how well it monitors progress toward the particular vision and goals in the regional context. Thus, findings in the previous studies indicate that the sustainable development priorities of a region can be appropriately extracted from articulated regional development goals and objectives, and incorporated into regional transportation planning using evaluation procedures whose parameters reflect these priorities. These guidelines are used as the basic concepts for formulating the methodology below.

5.1. Overview of the Methodology

Sustainability considerations can be effectively considered in regional transportation planning with the following steps: 1) identifying pertinent sustainability issues and regional sustainability goals for the metropolitan region of interest, 2) defining relevant performance measures for transportation system sustainability based on the predetermined issues and goals, 3) analyzing and quantifying the comprehensive sustainability impacts of alternative transportation and land use scenarios developed for the region, 4) constructing a Composite Sustainability Index (CSI) using multiple criteria decision making (MCDM) methods, and 5) visualizing the sustainability indexes using a decision support tool in order to identify the most sustainable plan for predetermined objectives. Figure 17 below depicts this procedure.

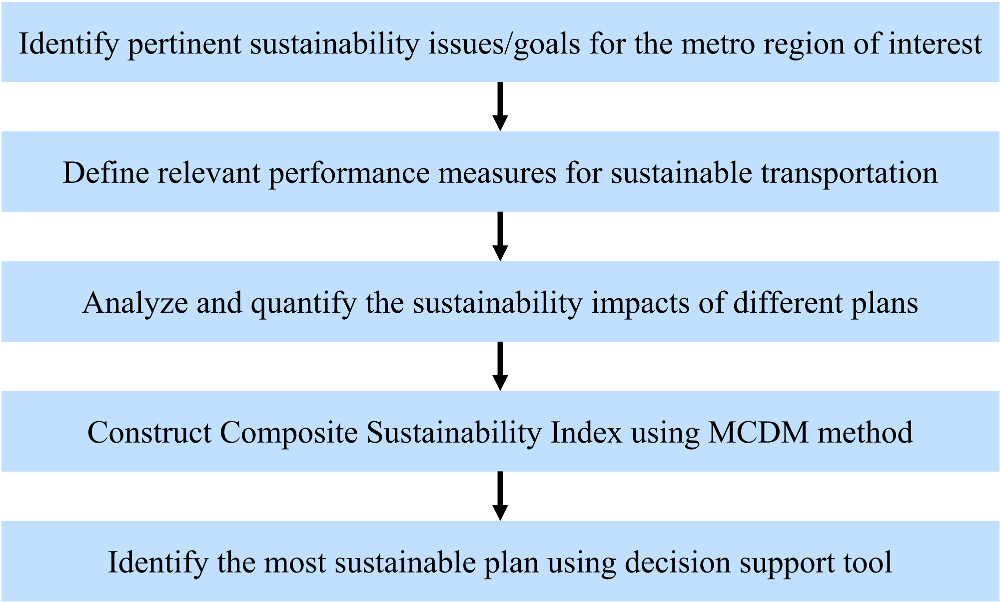

Figure 17 Sustainability Planning Framework

The core element of this framework is the CSI tool combined with the MCDM method. Considering the four essential dimensions of sustainable transportation system as system effectiveness, environmental, economic, and socio-cultural sustainability, the following profile graph can be used as a practical decision support tool (See Figure 18). A full diamond shape is considered to be the highest impacts of sustainability achievable for scenarios evaluated based on the current sustainability goals and objectives for the region. The area of each diamond conveys the relative level of sustainability. Using the visual index tool, decision makers can identify clearly superior alternatives but also consider tradeoffs that multiple scenarios present relative to the different sustainability dimensions.

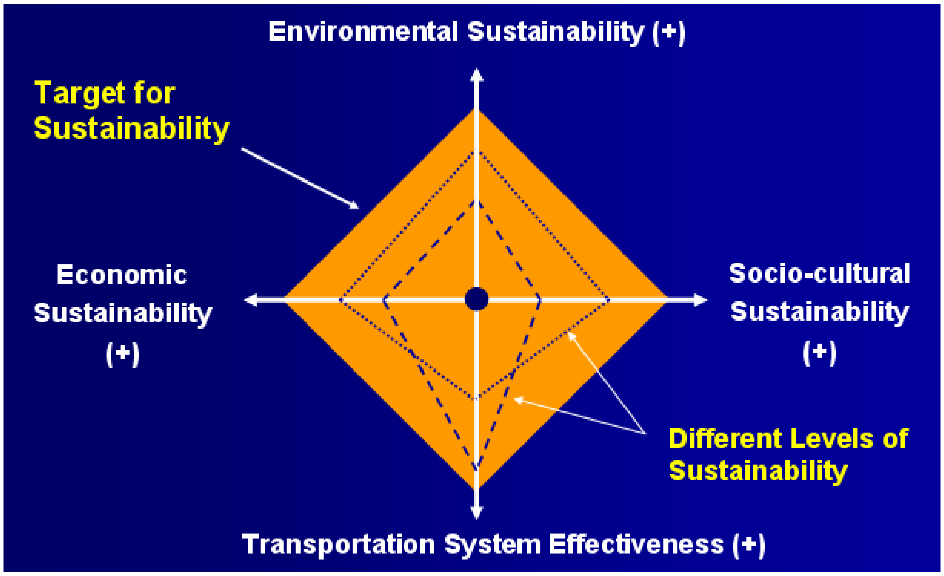

Figure 18 Visual Composite Sustainability Index Tool

5.2. Data and the Regional Context

This study demonstrates an application of the MCDM approach for incorporating sustainability considerations into the planning process in the metropolitan Atlanta region. The Atlanta Regional Plan goals and objectives are used to determine relevant sustainability dimensions and performance measures in order to capture the comprehensive sustainability concept in the regional planning context. An adopted regional transportation plan that results from the traditional four-step travel demand modeling process is combined with selected future land use scenarios and these integrated "test" scenarios are used for the actual evaluation. Two future scenarios: Mobility 2030 and Test Case 2030 are created by combining the adopted Regional Transportation Plan (RTP) with two land use scenarios: the Mobility 2030 and Draft Local Aspirations. As discussed in the introduction, the transportation network for the Draft Local Aspirations scenario was unavailable during the analysis period. Thus, while the test cases are useful for demonstrating the methodologies applied, the results of the analysis should be taken in the context of the limitation introduced by using the same transportation network for the different land use scenarios. Selected performance measures are evaluated to compare not only their overall sustainability, but also the tradeoffs that are being made in the different dimensions of sustainability (i.e., transportation system effectiveness, environmental, economic, and social sustainability) across the scenarios. Based on the discussion in chapter 3, the performance measures are derived from the regional priorities for sustainable development in the Metro area under consideration. Finally, this study identifies preferred scenarios from the point of view of advancing the region toward sustainability (i.e., comparatively superior plans among competing transportation plans for the predetermined sustainability-oriented objectives).

5.2.1. Atlanta Metropolitan Region, Georgia

With a land area of 57,906 square miles (149,976 km^2), Georgia is the largest state east of the Mississippi River (24th overall). The population of Georgia is almost 9 million, making it the 10th most populous state. Georgia’s population has grown 36% (2.35 million) from its 1990 levels, making it one of the fastest-growing states in the country. More than half of the state's population lives in the Atlanta metropolitan area which has experienced phenomenal growth in the past decade with total population approaching 5 million, making it the ninth largest metropolitan area in the United States. Atlanta is arguably a poster-child for cities worldwide experiencing rapid urban sprawl, population growth, and commercial development (Wikipedia.com, 2004).

Figure 19 shows the analysis area encompassing 13 counties and 1,683 traffic analysis zones (TAZ) in metro Atlanta. The mission of Georgia DOT is to provide a safe, seamless, and sustainable transportation system that supports Georgia’s economy and is sensitive to its citizens and environment. Among the DOT mission statements reviewed in 2005, Georgia's mission statement turned out to be the only one that explicitly incorporated the word "sustainability." More than half of the state's population lives in the metro area and it is expected to grow to 6 million people and with the employment of 3.3 million by the year 2030 ((ARC) 2006).

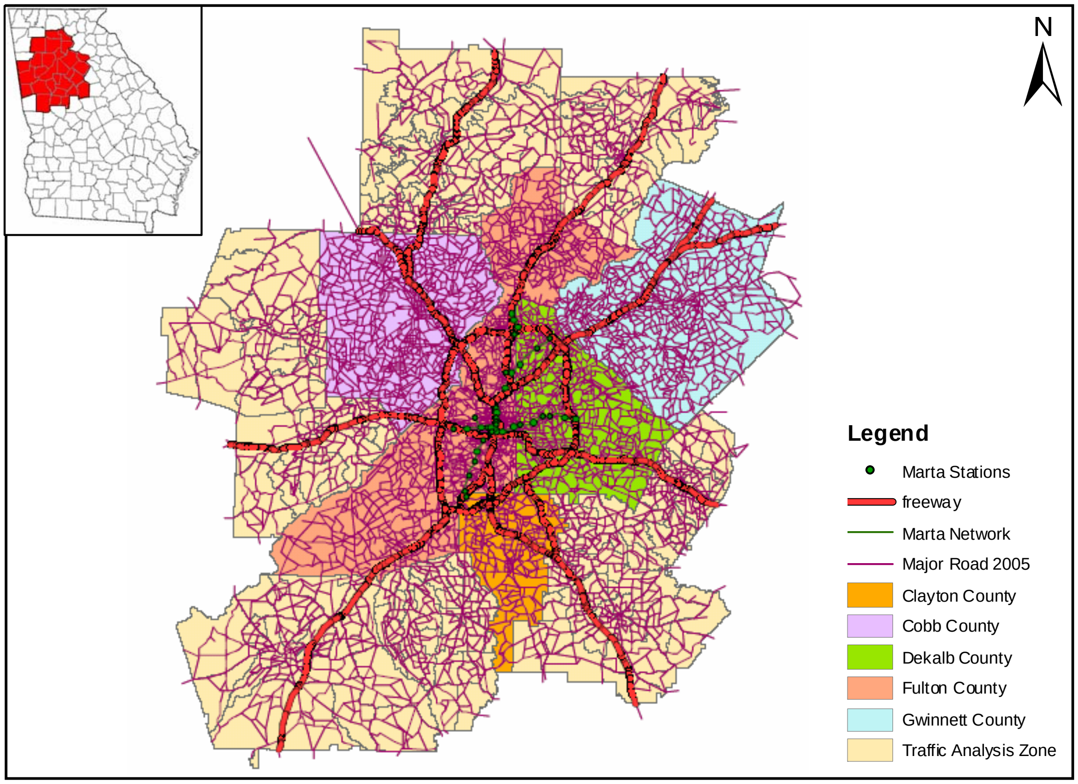

Figure 19 Atlanta Metropolitan 13-county Region

5.2.1.1. Pertinent Sustainability Issues in the Atlanta Metropolitan Area

The Atlanta region is one of the fastest growing areas in the United States. The region grew by 1 million people between 1990 and 2000, an average of 100,000 new residents per year. Employment grew by 63,000 jobs per year (ARC, 2006b). Population and employment growth will continue to drive increased trip making. Over 2.5 million people and an additional 1.3 million jobs are forecast between 2000 and 2030 (ARC, 2004). Expansion of the region's urbanized area will continue to create complex travel patterns, with no single center of population and employment dominating the region. Much of the new growth will continue to occur at low densities, which are not conducive to modes of travel other than the single occupant vehicle, and high density development will occur in distinct centers that do not have sufficient urban infrastructure (ARC, 2006b).

Limited transit options and high automobile dependency are considered intertwined problems in the region, as evidenced by automobile share at 94% of total home-based work trips (ARC, 2006b). Metro Atlanta faces severe congestion, with associated air quality and respiratory health issues. Roadway congestion and traffic delay have been estimated to cost Metro Atlanta residents 101 million person-hours of delay every year, equating to two billion dollars in total delay costs annually (TTI Homepage). According to the Texas Transportation Institute, the travel time index (traffic delay and congestion costs) has increased over 26% in the past eight years and Metro Atlanta has the 11th most congested freeway system in the United States. As of 2005, the 13-county non-attainment area for the one-hour ozone standard, in place for the last 15 years, was also revoked. An expansion of the Atlanta non-attainment area includes 20 counties with respect to a revised, stricter eight-hour ozone standard. In addition, a new fine particulate matter standard ($PM_{2.5}$) is now in place, and its non-attainment area includes the 20-county plus a small portion of outer counties. Other issues include social equity concerns related to minority groups, income level, the elderly, and disabled, and water consumption and erosion problems.

5.2.1.2. Regional Transportation Plan: Mobility 2030

The most recent transportation plan adopted by the Atlanta Regional Commission is referred to “Mobility 2030” and deals with the current and expanded demands being placed on the region’s transportation system. Listing the transportation projects for the next 25 years, Mobility 2030 satisfies the federal planning requirements for a metropolitan area such as Atlanta, and meets federal air quality requirements for a transportation plan to be in conformance with the region’s air quality plan. The plan is financially constrained in the sense that the recommended projects and investment strategies reflect the expected level of funding that will be available (ARC, 2005).

Based on the above sustainability issues, the long-range regional transportation plan, Mobility 2030, has the following goals:

1. Improving accessibility and mobility,
2. Maintaining and improving system performance and preservation,
3. Protecting and improving the environment and quality of life, and
4. Increasing safety and security.

These goals basically address a wide range of regional issues related to accessibility, mobility, system performance and preservation, environment, quality of life, safety, and security. In the next chapter, the study also discusses whether these Mobility 2030 goals are sufficient for characterizing progress toward sustainability and how well the existing goals capture the concept of sustainability.

Demand forecasting models used in Mobility 2030 are prepared using data from the SMARTRAQ (Strategies for Metropolitan Atlanta’s Regional Transportation and Air Quality) Household Travel Survey conducted in 2000. The trip generation model uses a new approach that is based on a set of logit models for estimating the probability of a person making no trips, 1 trip, 2 trips, etc. The trip distribution model uses a common gravity-based model with a composite time that considers highway and transit times. The mode choice model employs a nested logit formulation for all person trip purposes. TP-Plus, the renowned travel demand forecasting software, is used to model and control these core modeling systems as shown in Figure 20 (ARC, 2003).

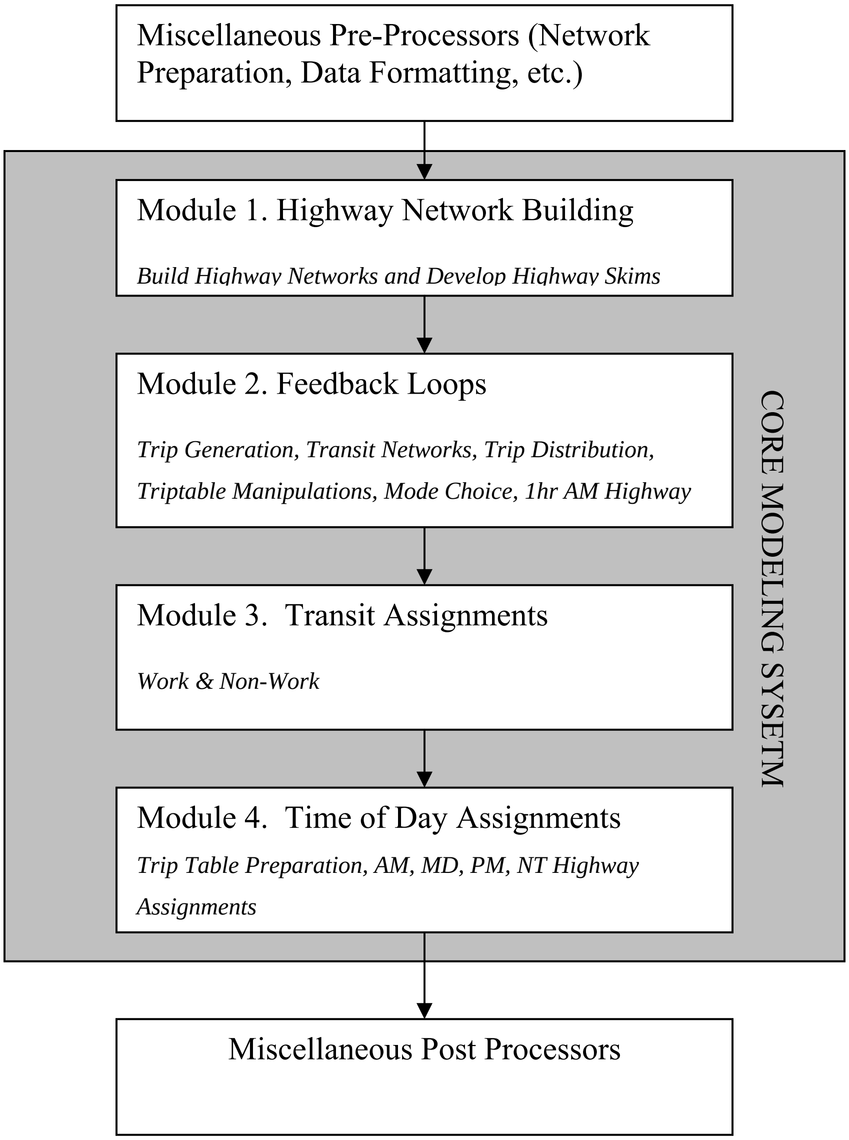

Figure 20 Generalized Atlanta Model Flow Chart
(Source: ARC, 2003)

5.2.1.3. Regional Initiative on Land Use Scenarios: Envision 6

There has been new interest and significant progress in the state of the art of integrated urban land use and transportation modeling as discussed in Jeon et al. (2007). The Atlanta Regional Commission (ARC) appears to be in step with this trend and has launched the Envision 6 Program, which essentially attempts to integrate land use planning and transportation planning as it updates the Regional Transportation Plan (RTP). Envision 6 has been used in developing several integrated transportation and land use scenarios using the INDEX software based on a series of stakeholder meetings, regional charrettes with various stakeholders, and web and telephone surveys (ARC, 2006a). The land use scenarios developed in this process were based on local input and utilized adopted future land use maps as the foundation. Thus, these land use scenarios involve multiple issues such as water and sewer, environmental issues, transportation, and schools. As of May, 2006, ARC has developed three different land use scenarios by reviewing adopted future land use maps and discussing current growth patterns and local aspirations for directing future growth with elected officials, planners, transportation engineers, water and sewer staff, and school planners. The following land use scenarios developed through the Envision 6 Program, are discussed in more detail below: 1) Adopted RTP Forecast Scenario -- Mobility 2030, 2) Local Future Land Use Scenario -- Compilation of Locally Adopted Comprehensive Plans, and 3) the "Draft" Local Aspirations Scenario -- Summarized from Local Meetings. These scenarios are then reviewed and analyzed with current transportation system to determine the sensitivity of ARC's Travel Demand Model against the land use scenarios and to analyze the performance of Mobility 2030 and various land use performance measures (ARC, 2006b).

First of all, the Mobility 2030 scenario represents the population and employment forecasts used in the development of the adopted Mobility 2030 transportation plan (ARC, 2006a). The scenario over-exaggerates job growth as a result of the manner in which the forecast model characterizes job density. Overall, the setting depicts a region that has substantial job growth in both core areas and suburbs. Characteristics of this scenario include distribution of growth based on available land, trends, and policy; proportional allocation of jobs with new households; small percentage of land available in 2030; and even distribution of low density employment (ARC, 2006b).

Second, the local future land use scenario has similar population forecasts as the adopted 2030 RTP scenario detailed above, but it has significantly higher number of forecasted jobs and allocates most remaining vacant land in the region to low density residential development. Characteristics of this scenario include separation of jobs from households, decreased transit share, increased delay compared to Mobility 2030, and small percentage of available land in 2030 (ARC, 2006b).

Lastly, the draft Local Aspirations Plan scenario is a centers- and corridor-based approach with growth concentrated along the major roadways, interchanges, and exiting urban centers. This scenario uses local future land use plans, water and sewer plans, and other local policy as its foundation, but has been significantly influenced based on the input ARC received at the 17-county jurisdiction meetings with elected officials and staff. In many cases, when asked to identify the locations appropriate for development to accommodate the population and job growth anticipated in the county, local officials and staff situated growth along corridors and activity centers. Characteristics of this scenario include higher density residential located closer to jobs along corridors and in activity centers; a higher percentage of housing accessible to transit; a higher percentage of rural land and green space; and a lower percentage of low density housing construction. The draft Aspirations scenario represents a diverse vision of local leaders, but represents a plan very different from the adopted future local land use plans (ARC, 2006b).

As of the beginning of 2006, the Envision6 Program is in the middle of its three year process to support the RTP update due by 2007 and the Regional Development Plan (RDP) update due by 2008 (ARC, 2006b). ARC is taking steps to create a new population forecast and a new transportation aspirations plan that implements a various alterations of transportation projects proposed in the adopted Mobility 2030. This ongoing process will in turn compliment the current land use scenarios by matching the transportation infrastructure system and other land use patterns (Personal Interview, 2006).

5.2.1.4. Selected Transportation and Land Use Scenarios

Based on the adopted RTP and newly developed draft land use scenarios, this study creates two future transportation and land use plans in addition to the present transportation and land use system, used as a benchmark. Thus, three transportation and land use plan alternatives of the Atlanta Metropolitan Region are to be evaluated in the study: (1) the Baseline 2005, (2) the Mobility 2030, and (3) the Test Case 2030. The Baseline 2005 alternative captures the benchmark of the present transportation and land use system as of 2005. The Mobility 2030 and the Test Case 2030 scenarios are created by overlaying the adopted RTP for 2030 with ARC's future land use scenarios from the Envision 6 Program. The Mobility 2030 plan alternative integrates the adopted RTP with the Mobility 2030 land use scenario, which uses the population and employment forecasts used in the development of the adopted RTP. The Test Case 2030 plan alternative integrates the adopted RTP with the draft Local Aspirations land use scenario, which is essentially developed from various local meetings. Thus, the Mobility 2030 and the Test Case 2030 have identical transportation planning outcomes/forecasts but different land use patterns (i.e., distribution of population and employment). Figure 21 provides a simple representation of two future transportation and land use plan alternatives, the Mobility 2030 and the Test Case 2030. High density employment areas are represented by red, medium to low density employment areas are coded by a range of yellow, and rural land and green space are coded by green. Apparently, the Test Case 2030 is a more concentrated plan alternative that higher density residential located closer to jobs along corridors and in activity centers contains a higher percentage of rural land and green space in the suburb. Thus, ideally, the transportation plan associated with the Test Case 2030 scenario ought to be aligned more closely with these assumptions.

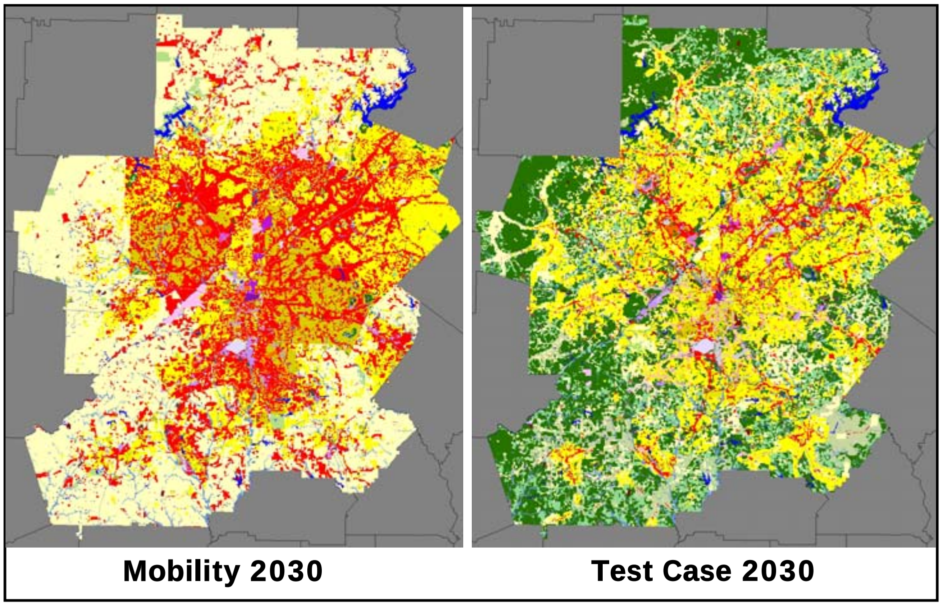

Figure 21 Selected Future Transportation and Land Use Scenarios

The next chapter evaluates transportation system sustainability of these selected transportation and land use scenarios using the proposed sustainability framework in this chapter. While the sustainability framework and evaluation process are applied to the Atlanta Metropolitan Region, they remain broadly applicable to other metropolitan areas.

CHAPTER 6

SUSTAINABILITY FRAMEWORK AND EVALUATION

From the previous chapter, incorporation of sustainability considerations into the regional transportation planning can be summarized as involving the following: 1) identifying pertinent sustainability issues and regional sustainability goals for the metropolitan Atlanta region, 2) defining relevant performance measures for transportation system sustainability based on the predetermined issues and goals, 3) analyzing and quantifying the comprehensive sustainability impacts of selected transportation and land use plans, 4) constructing a Composite Sustainability Index (CSI) using the multiple criteria decision making (MCDM) theory, and 5) visualizing the sustainability indexes using a decision support tool and identifying the most sustainable plan for predetermined sustainability-oriented objectives. Using the proposed sustainability framework, this chapter evaluates transportation system sustainability of the test scenarios created by integrating transportation and land use plan alternatives for metro Atlanta region, as well as the baseline 2005 conditions for the metropolitan transportation system. Thus, the three test scenarios used in the analysis are: the Baseline 2005 (i.e., the base case scenario), the Mobility 2030, and the Test Case 2030.

6.1. Pertinent Sustainability Issues and Goals

As depicted above the first step in this procedure is to identify existing sustainability issues and regional sustainability goals for the metro area being considered. This activity is an important starting point because the sustainable development priorities of a region can be appropriately extracted from regional sustainability issues and articulated regional development goals and objectives. At the same time, the relative effectiveness of sustainability evaluation is often considered to be a function of how well the evaluation process monitors progress toward the particular sustainability vision and goals in the regional context. It should also be noted that some sustainability goals are more superior to others with respect to reaching a particular vision.

A wide range of regional sustainability issues in Metro Atlanta includes limited transit options and high automobile dependency, resulting roadway congestion and traffic delay, air quality and respiratory health issues, social equity issues, and water consumption and erosion problems. Based on the above sustainability issues, Metro Atlanta's long-range regional transportation goals are articulated in the Mobility 2030 plan as the following: 1) improving accessibility and mobility, 2) maintaining and improving system performance and preservation, 3) protecting and improving environment and quality of life, and 4) increasing safety and security.

These goals basically address a variety of regional issues related to accessibility, mobility, system performance and preservation, environment, quality of life, safety, and security. Considering that mobility can be a subset of system performance, the existing goals appropriately incorporate the dimension of transportation system effectiveness. While the environmental dimension of sustainability is captured by the regional goals, the environmental perspectives could have been specified further with such measures as air quality, noise pollution, and fuel consumption. The social dimension of sustainability is also incorporated in the existing goals where accessibility, quality of life, safety, and security are addressed. Social equity and public health, however, are also important elements with respect to the social dimension and should be included to enhance the social component of the assessment. Economic goals are not explicitly articulated in the adopted RTP. The economic dimension of sustainability may be captured with such common goals and objectives as “maximizing economic efficiency,” “maximizing financial affordability,” and “promoting regional economic development.” Since the new development of transportation and land use positively influences regional accessibility and results in economic vitality, this important component will allow for a more comprehensive evaluation of transportation system sustainability. To summarize, the existing Mobility 2030 goals attempt to incorporate some important perspectives of transportation system sustainability, addressing transportation system effectiveness and environmental integrity. These goals, however, can be improved by specifying social equity and public health concerns from a social sustainability perspective which may be implied in the word “quality of life.” Some economic vision may also need to be included in the goal in order to effectively address the economic dimension of sustainability with the objectives of economic efficiency, financial affordability, and regional economic development.

6.2. Relevant Sustainability Definitions and Performance Measures

Based on the regional goals and prior literature review, transportation system sustainability should at the very least incorporate attributes of system effectiveness and system impacts on the economic development, environmental integrity, and the social quality of life (Jeon and Amekudzi 2005). Thus, this study considers the four essential dimensions of sustainability as transportation systems effectiveness, economic sustainability, environmental sustainability, and social sustainability.

Discussed extensively in Chapter 4, necessary factors of transportation system effectiveness include system performance for multimodal transportation systems such as regional highways and transit systems. Necessary environmental factors for sustainability include resource preservation (such as fossil fuels and land), air and noise pollution prevention, and greenhouse effect prevention for global sustainability issues associated with the livability of current and future generations. Necessary economic factors for sustainability include economic efficiency, financial affordability, and regional economic development attained by improving accessibility. Necessary social factors for sustainability include social equity related to income and minority groups, public health, safety and security, accessibility to various services, and all these four factors inevitable affect the overall quality of life.

Performance measures can be determined on the basis of these necessary factors and should be also influenced by regional goals and objectives in order to take into account sustainability issues identified as relevant. Table 25 shows the existing goals categorized into each dimension of sustainable transportation and the appropriate performance measures that address the different goals. It is noteworthy that transportation system effectiveness is included with the three basic dimensions of sustainability because transportation mobility and system performance are indispensable components of transportation system sustainability. Moreover, system effectiveness may often be considered a fundamental criterion for system sustainability in that planners have regarded effectiveness as the starting point and other perspectives as optional, additional criteria. Decision makers, however, should take into consideration not only system effectiveness impacts but also environmental, economic, and social impacts of selecting one plan over another in order to plan for more sustainable future.

Table 25 Selected Sustainability Goals and Performance Measures

Sustainability Dimension	Goals and Objectives	Performance Measures
Transportation System Effectiveness	A1. Improve Mobility	A11. Freeway/arterial congestion
	A2. Improve System Performance	A21. Total vehicle-miles traveled A22. Freight ton-miles A23. Transit passenger miles traveled A24. Public transit share
Environmental Sustainability	B1. Minimize Greenhouse Effect	B11. CO_2 emissions B12. Ozone emissions
	B2. Minimize Air Pollution	B21. VOC emissions B22. CO emissions B23. NO_X emissions
	B3. Minimize Noise Pollution	B31. Traffic noise level
	B4. Minimize Resource Use	B41. Fuel consumption B42. Land consumption
Economic Sustainability	C1. Maximize Economic efficiency	C11. User welfare changes C12. Total time spent in traffic
	C2. Maximize Affordability	C21. Point-to-point travel cost
	C3. Promote Economic development	C31. Improved accessibility C32. Increased employment
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

The performance measures defined in Table 25 are considered to be feasible and comprehensive in the sense that one can actually evaluate the level of sustainability while considering the comprehensive dimensions of transportation system sustainability. Thus, these wide-ranging measures are quite different from those used in conventional transportation planning, i.e., congestion, mobility, and minimal environmental concerns (air quality indicators generally). Each goal and objective is represented by one or more performance measures. Mobility, which is a subset of the system effectiveness goal, is captured by average freeway or arterial speed, for example. Similarly, air pollution is represented by emissions of two ozone precursors (VOC and NO_X) and CO; economic efficiency is represented by user welfare changes and total time spent in traffic, and public health is represented by human exposure to emissions and noise.

6.3. Selected Sustainability Performance Measures and Their Evaluation

This study attempts to evaluate a feasible numbers of performance measures from the full indicator list (shown as in Table 25) within the scope of this dissertation. In other words, the performance measures actually evaluated to capture the sustainability goals and objectives of the Atlanta Metropolitan Region are a limited set from this indicator list. Figure 22 illustrates these selected performance measures categorized into each sustainability dimension and goal. Sections below discuss how these individual performance measures are evaluated and identify some findings and implications drawn from performance measurement on regional sustainability. Further development and quantification of sustainability measures will help incorporate the sustainability considerations more fully.

6.3.1. Transportation System Effectiveness Indicators

Average freeway speed (A11) and vehicle miles traveled per capita (A21), the average distance each person in the region drives each day, are selected to capture elements of transportation system effectiveness. Average freeway speed is often used as a proxy for freeway congestion, so it may not fully represent the level of mobility despite its popularity. System performance, including mobility and reliability, is considered to be

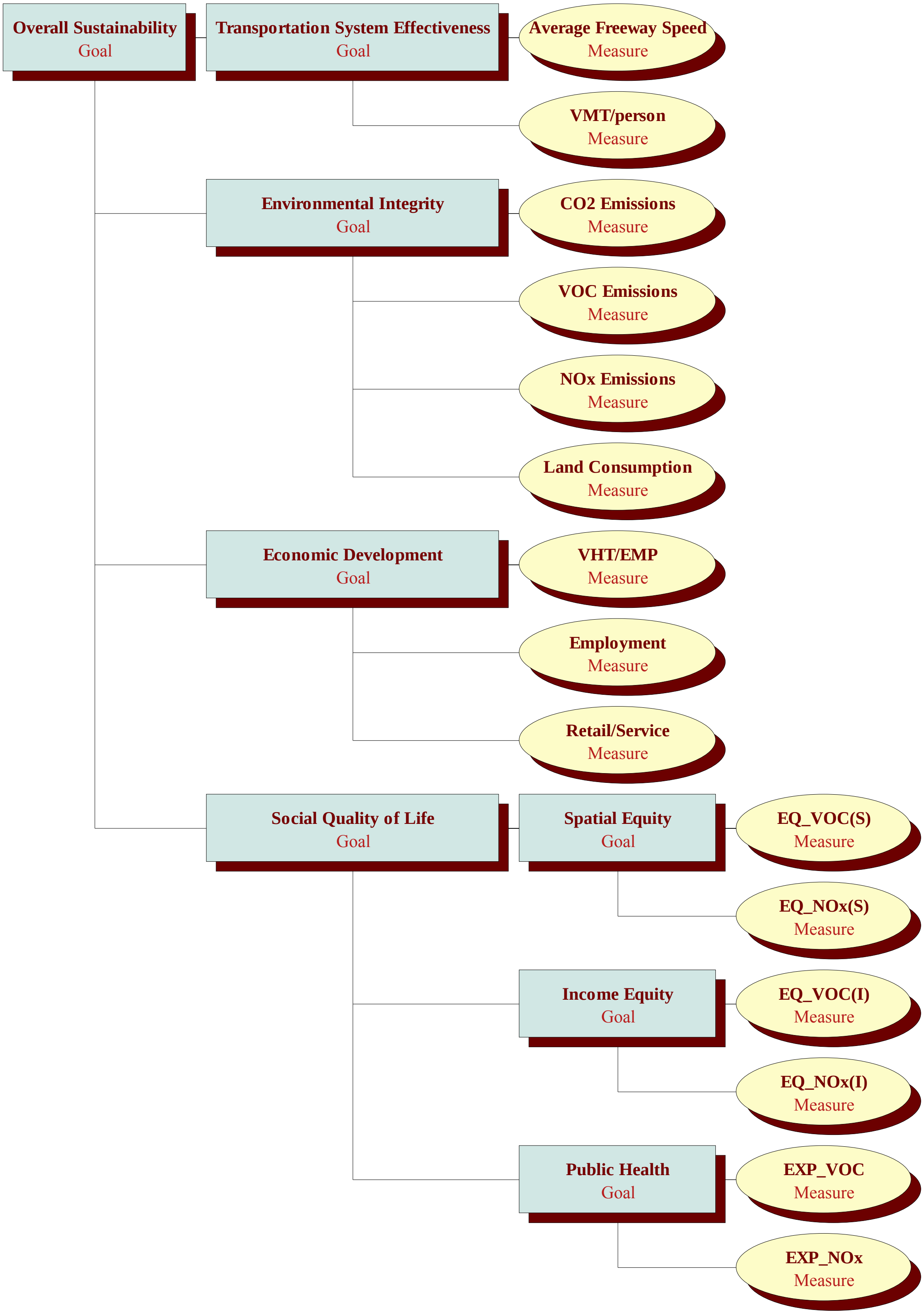

Figure 22 Selected Performance Measures categorized into Sustainability Dimensions.

better when average freeway speed is higher and vehicle miles traveled per person are less, respectively. Not surprisingly, these two indicators are often found to be negatively correlated: average freeway speed would increase as vehicle miles traveled per capita decreased. However, there may be an exceptional case where vehicle miles traveled per capita can also be low due to poor mobility.

Table 26 compares average freeway speed, total vehicle miles traveled (VMT) per day, and total VMT per day per capita for three selected scenarios: Baseline 2005, Mobility 2030, and Test Case 2030. The baseline average freeway speed of the system is 47.12 mile/hour (2005) -- the highest among the three scenarios -- while the forecast speed of two future scenarios are both 42.21 mile/hour, 10 percent lower than the baseline speed. The total vehicle miles traveled for the baseline scenario is 129 million miles per day while the future values are estimated much higher at 191 million miles per day. Daily vehicle miles traveled per capita is computed as the total daily VMT divided by the total population for the 13-county Atlanta area. The total VMT per capita is 35.04 miles for the baseline and 31.75 and 32.61 miles for the Mobility and Test Case 2030 plans, respectively. Population will increase significantly from 3.7 million to 6 million; however, average freeway speed only decreases by 10 percent primarily resulting from the decrease in total VMT per capita.

Table 26 System Effectiveness Measures

	Average Freeway Speed (Mile/Hour)	Total Vehicle Miles Traveled (Mile/Day)	Population	Total VMT Per Capita (Mile/Day/Person)
Baseline 2005	47.12	129,049,330.3	3,682,507	35.04
Mobility 2030	42.21	190,939,512.8	6,014,618	31.75
Test Case 2030	42.21	190,939,512.8	5,854,968	32.61

6.3.2. Environmental Sustainability Indicators

Table 27 shows total daily emissions of CO_2, VOC, and NO_x in grams for the three selected scenarios: Baseline 2005, Mobility 2030, and Test Case 2030. Total CO_2 emissions of the baseline scenario are 72.3 tons per day while those of future scenarios are 110.8 tons per day, 53 percent higher than the present. For the calculation of total daily emissions for a particular year, emission rates estimated for the corresponding year are used, i.e., the 2005 fleet is used for evaluating Baseline 2005 while the 2030 fleet is used for evaluating two future scenarios. The intent in this table is to compare the emissions impacts associated with the current transportation and land use systems with the 2030 forecast associated with future sustainability.

Table 27 Total Daily Emissions of Air Pollutants

	Total CO_2 (gram/Day)	Total VOC (gram/Day)	Total NOx (gram/Day)
Baseline 2005	72,306,339,759	118,328,710	209,637,092
Mobility 2030	110,764,011,387	53,375,690	38,330,555
Test Case 2030	110,764,011,387	53,375,690	38,330,555

However, it is important to keep in mind that while the 2030 values reflect an element of environmental sustainability, the 2005 values do not. The emissions presented for the 2005 Base Case are not a measure of relative sustainability related to non-technological improvements because even if Atlanta were to experience no population growth, no road construction, and no change in vehicle miles of travel between 2005 and 2030, the natural effect of vehicle fleet turnover (retirement of existing vehicles and purchase of new replacement vehicles) will decrease total VOC and NO_x emissions by 55 percent and 82 percent, respectively, between the baseline and future dates without any change in policy. Hence, the difference between the 2005 and 2030 values in the Table are not an indicator of the superiority of future scenarios over a no action alternative outside the improvements in the vehicle fleet. The improvement in total daily emissions of VOC and NO_x between 2005 and 2030 mainly results from the decrease in emission rates associated with vehicle technology improvements (i.e., cleaner vehicle engine, improved fuel efficiency) that come with fleet turnover. Throughout this study, it is assumed that future improvements in technology, life style, etc. should also be considered in line with the improved quality of life and sustainability.

As discussed in Chapter 1, Section 4, although the two 2030 land use scenarios provided by the planning agency were different, at the time the analyses were conducted the new travel demand model outputs were not available. Hence, the two 2030 scenarios presented here still employ the same number of vehicle trips, network traffic volumes, and on-road operating conditions (congestion levels and resulting on-road vehicle speeds). Because the two scenarios employ the same emission rates for 2030 and the same assumptions related to emissions-producing vehicle activity, the projected mass emissions are the same for the two scenarios. Given that the two land use scenarios are different, the travel patterns for the actual plans will be different, and the actual emissions impacts of the final 2030 scenarios being prepared by the regional planning agency will be different when they are complete.

Table 28 represents an amount of land consumed by transportation infrastructure systems, such as right-of-way and parking lots, for the three selected scenarios. Land consumed by right-of-way is 19,300 acres for Baseline 2005 and Mobility 2030 while it is 20,800 acres for the Test Case 2030 scenario, representing an increase of 8 percent. Land consumed by parking lots, structures, or utilities is 11,200 acres, 10,900 acres (3 percent decrease from the Baseline scenario), and 10,200 acres (9 percent decrease from the baseline scenario) for the Baseline, Mobility 2030, and Test Case 2030, respectively. Thus, land consumed by transportation infrastructure systems is estimated by summing these two measures both of which evaluate how much land should be devoted to different transportation plans. Land consumption measures show 30,500 acres (1.18% of total land area) for the present, 30,200 acres (1.17% of total land area) for Mobility 2030, and 31,000 acres (1.2% of total land area) for Test Case 2030. Mobility 2030 takes up 1 percent less land than Baseline 2005 while Test Case 2030 occupies 1.5 percent more land than Baseline 2005. These land consumption measures do not represent significant differences among the selected three scenarios.

Table 28 Land Consumed by Transportation Infrastructure

	Right-of-Way (Acre)	Parking Lot (Acre)	Sum (Acre)
Baseline 2005	19297.6	11215.4	30,513.1 (1.18% of Total)
Mobility 2030	19297.3	10918.7	30,215.9 (1.17% of Total)
Test Case 2030	20807.9	10160.2	30,968.1 (1.20% of Total)

6.3.3. Economic Sustainability Indicators

Vehicle hours traveled per capita (C12), the average duration each person in the region drives each day, is chosen as a surrogate measure for total time spent in traffic. A transportation plan with fewer vehicle hours traveled per person per day is regarded as a more efficient and economically productive plan. Other freight measures would be essential for capturing economic sustainability; however, the evaluation of these measures cannot be included due to limited data sources.

Table 29 shows daily vehicle hours traveled (VHT) and normalized measures including VHT per capita as well as VHT per employment. Daily vehicle hours traveled per capita or per employment are computed as the total daily VHT divided by the total population or employment for the 13-county Atlanta area. Daily VHT for the Baseline is 568,172 hours while daily VHT for the year 2030 is 897,380 hours with an increase of 58 percent. Measures of VHT per capita do not represent a significant difference between the Baseline and the future, both of which are estimated to be approximately 9 minutes. However, measures of daily VHT per "employment" differ considerably from 13 minutes (for the Baseline) to 16 minutes (for the future) with an increase of 26 percent. It is noteworthy that daily VHT per population decreases slightly over time while daily VHT per employment increases significantly over time. Considering that daily VHT per employment is a more realistic estimate for commute travel, the average time each employee in the region drives each day increases 26 percent between the Baseline and the future.

Table 29 Vehicle Hour Traveled Indicator

	Daily Vehicle Hours Traveled (Hour)	Daily VHT per capita (Minute)	Daily VHT per employment (Minute)
Baseline 2005	568,172 (23,674 days)	9.26	12.91
Mobility 2030	897,380 (37,391 days)	8.95	16.22
Test Case 2030	897,380 (37,391 days)	8.95	16.22

Table 30 represents population and employment for 2005 and 2030. Transportation and land use decisions may induce growth in the population and employment, so increased job opportunities can be a measure of the regional development impact of new plan alternatives. The Mobility 2030 plan increases employment by 679,100 jobs: 26 percent of employment growth relative to the base year 2005. The Test Case 2030 plan increases employment by 671,500 jobs: 25 percent of employment growth relative to the base year 2005. Thus, these two future plans seem to positively influence regional economic development by encouraging relatively similar levels of economic activity in the region.

Table 30 Employment Increase Effect

	Population	Employment	Employment/ Population
Baseline 2005	3,682,507	2,640,609	0.72
Mobility 2030	6,014,618 (63% increase)	3,319,707 (26% increase)	0.55
Test Case 2030	5,854,968 (59% increase)	3,312,122 (25% increase)	0.57

Table 31 shows land consumption by regional activity centers including regional centers, retail and services, and mixed land use relative to total land area. Baseline 2005 consumes about 6 percent of total land for regional activity centers while the two future plans significantly increase land consumption. Mobility 2030 especially shows a considerable increase of land consumption (230 percent) by business purpose as 20 percent of total land is devoted to regional economic activities. Test Case 2030 also increases land consumed by retail and services by 34 percent which results in an allocation of 8.4 percent of the total land available for business purposes.

Table 31 Land Consumed by Retail and Service

	Land consumed by Retail/Services (Acre)	Total Land Area (Acre)	Ratio
Baseline 2005	161,663	2,578,490	6.3%
Mobility 2030	532,637 (230% increase)	2,578,271	20.1%
Test Case 2030	217,170 (34% increase)	2,578,456	8.4%

6.3.4. Social Sustainability Indicators

Social equity can be captured by equity of exposure to emissions (D12) and public health is represented by exposed population to emissions (D21). Actual exposure to pollutant concentrations is beyond the scope of the current analyses, due to the complex nature of predicting hourly pollutant concentrations and population movements for exposure assessment. However, as exposure models continue to evolve, this metric can be fully incorporated into the sustainability metric. Until adequate modeling tools can be approved for regulatory analysis, surrogate measures may be used, which are highly simplified in some cases, but capture some of the core characteristics.

6.3.4.1. Equity of Exposure to VOC and NO_x Emissions (D12)

The potential differential equity that may result from alternative transportation plans is evaluated using the equity of emissions distribution relative to (1) the geography and (2) different income levels. The goal of these metrics is to assess the spatial distribution of pollutant concentrations relative to the home locations of various demographic/income groups for exposure to toxic air contaminants.

6.3.4.1.1. Spatial Equity Indexes (D12-1)

The spatial equity indexes are derived by ordering 1,683 TAZs from the highest to lowest emission densities and plotting the cumulative percentage of total land area against the cumulative percentage of pollutants (FHWA, 2006). Emission densities are calculated by dividing total emissions contained by the land acre of each TAZ, assuming that each TAZ is exposed to the amount of VOC and NO_x emissions resulting from the transportation links located within a particular TAZ. The higher the index is, the greater the spatial equity that can be achieved.

Figure 23 depicts how spatial equity indexes can be derived from spatial concentration of VOC and NO_x emissions for Baseline 2005. Ninety percent of transportation-related VOC and NO_x emissions in the region are concentrated on merely about 20 percent of total land, which implies severe inequity on emission distribution geographically. Such spatial inequity negatively influences regional sustainability from a social standpoint with public health implications.

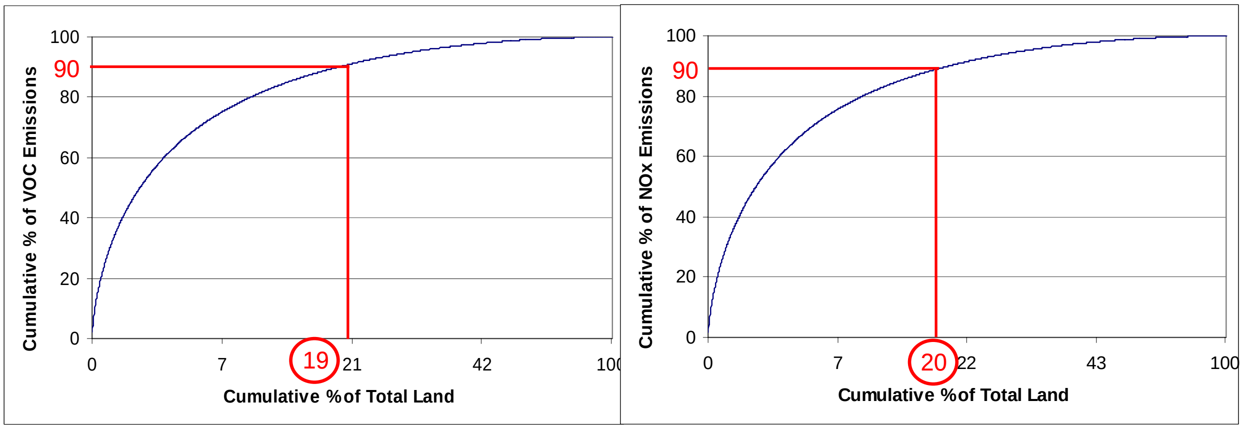

Figure 23 Spatial Equity Indexes of VOC and NO_x emissions: Baseline 2005.

Figure 24 shows how spatial equity indexes can be derived from spatial concentration of VOC and NO_x emissions for the future year of 2030. Ninety percent of transportation-related VOC and NO_x emissions in the region will be concentrated on about 24 percent of total land if decision makers adopt either Mobility 2030 or Test Case 2030. There still exists severe spatial inequity for emissions distribution since toxic air contaminants are concentrated merely on one fourth of total land. However, the spatial equity indexes indicate a slight improvement on spatial equity on emissions distribution over the geography compared to the baseline scenario.

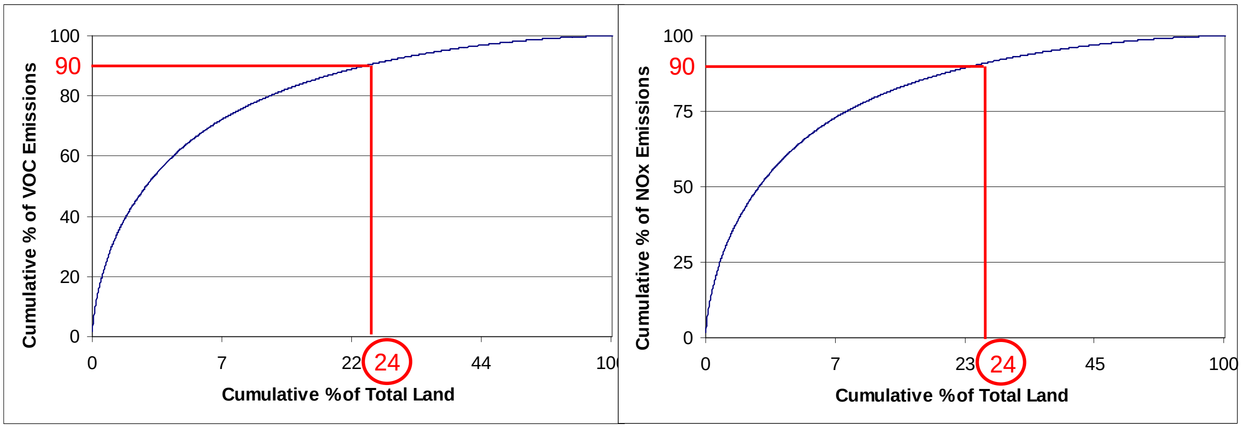

Figure 24 Spatial Equity Indexes of VOC and NO_x emissions: Mobility/Test Case 2030.

Alternatively, the spatial equity index of VOC emissions can singly be used as a surrogate measure for toxic air contaminants. It is important to note that a measure related to the spatial equity of fine particulate matter emissions should also be incorporated in future analysis.

6.3.4.1.2. Income Equity Indexes (D12-2)

The income equity index quantifies the difference of share between four income levels and the emissions concentration for each income level. The percentage of households with low income (less than \$20K), low medium income (\$20K-\$50K), high medium income (\$50K-\$100K), and high income (more than \$100K) are individually considered for the specific analysis year (ARC, 2004). The income equity indexes are calculated from the following equation:

$$100 - \sum_i \left| X_i - Y_i \right|$$

where X_i is percentage of low, low medium, high medium, and high income households and Y_i is percentage of emission concentration for each income classes. The lower the index is, the greater the gap between income and emission distribution.

Figure 25 shows how income equity indexes can be derived from comparing distribution of income groups and corresponding emission concentration for each income group for the base year 2005. In the Baseline scenario, the percentage of households with low income, low medium income, high medium income, and high income are 15%, 30%, 35%, and 20%, respectively. Baseline 2005 does not result in a significant disparity between income distribution and VOC and NO_x emission distribution: the percentage of emission exposure for low to high income groups are 16%, 32%, 34%, and 18%, respectively. The income equity index for VOC emissions is estimated at 93.7 percent while income equity index for NOx emissions is 94 percent. However, there is a tendency that low and low medium income people are exposed to higher level of emissions than they should be while high medium and high income people are exposed to lower level of emissions than they should be. Even though income equity indexes indicate a small amount of inequity, it is noteworthy that households with low and low medium income are more likely to have disproportionately high exposure while households with high and high medium income are more likely to be beneficiaries.

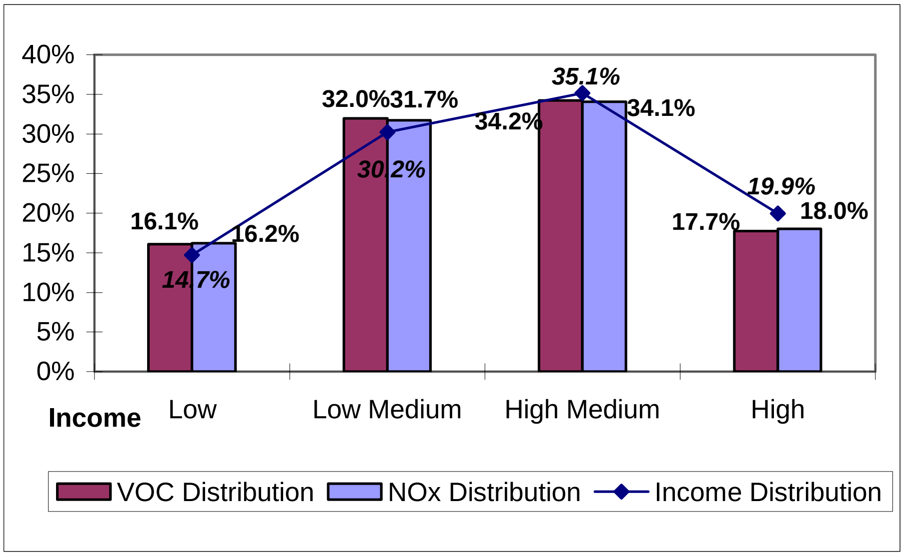

Figure 25 Income Equity Indexes of VOC and NOx emissions: Baseline 2005.

Figure 26 shows the distribution of income groups and corresponding emission concentrations for each income group for Mobility 2030 alternative. The percentage of households with low income, low medium income, high medium income, and high income are 12.3%, 29.1%, 37.2%, and 21.4%, respectively. Compared to the present, households with low and low medium income decrease by 3.3 percent while households with high medium and high income increase by 3.6 percent. Mobility 2030 results in slightly more disparity between income distribution and VOC and NO_x emission distribution compared to the Baseline. The percentage of VOC emission exposure for low to high income groups are 18.6%, 28.1%, 33.7%, and 19.6%, respectively while the percentage of NO_x emission exposure for low to high income groups are 18.4%, 29%, 33.4%, and 19.3%, respectively. The income equity index for VOC emissions is estimated at 87.4 percent while income equity index for NOx emissions is 88 percent. These indexes indicate an increased inequity level of 6.3 percent (VOC emissions) and 6 percent (NO_x emissions) compared to the Baseline. The results reveal that low income groups are exposed to 50 percent higher level of emissions than they should be while low medium, high medium, and high income people are exposed to lower levels of emissions than they should be. It is noteworthy that households with low income (about 12 percent of total) are more likely to have disproportionately higher exposure while the remaining households with medium and high income (about 88 percent of total) are more likely to be beneficiaries.

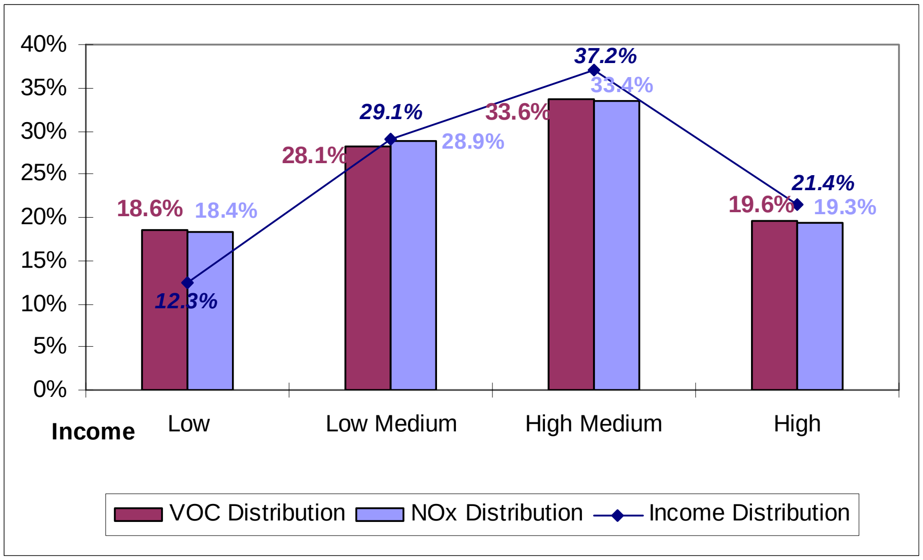

Figure 26 Income Equity Indexes of VOC and NOx emissions: Mobility 2030.

Figure 27 shows the distribution of income groups and corresponding emission concentrations for each income group for the Test Case 2030 alternative. According to this scenario, the percentage of households with low income, low medium income, high medium income, and high income are 15.5%, 31.8%, 33.8%, and 18.9%, respectively. Compared to the Baseline, households with low and low medium income increase by 2.4 percent while households with high medium and high income decrease by 2.3 percent. It is quite interesting that Test Case 2030 results in an increase of lower income households along with a decrease of higher income households. For some reason, Test Case 2030 results in severe disparities between income distribution and VOC and NO_x emission distribution compared to the Baseline. The percentage of VOC emission exposure for low to high income groups are 33.4%, 24.4%, 28.5%, and 13.7%, respectively while the percentage of NO_x emission exposure for low to high income groups are 32%, 25.5%, 28.8%, and 13.6%, respectively.

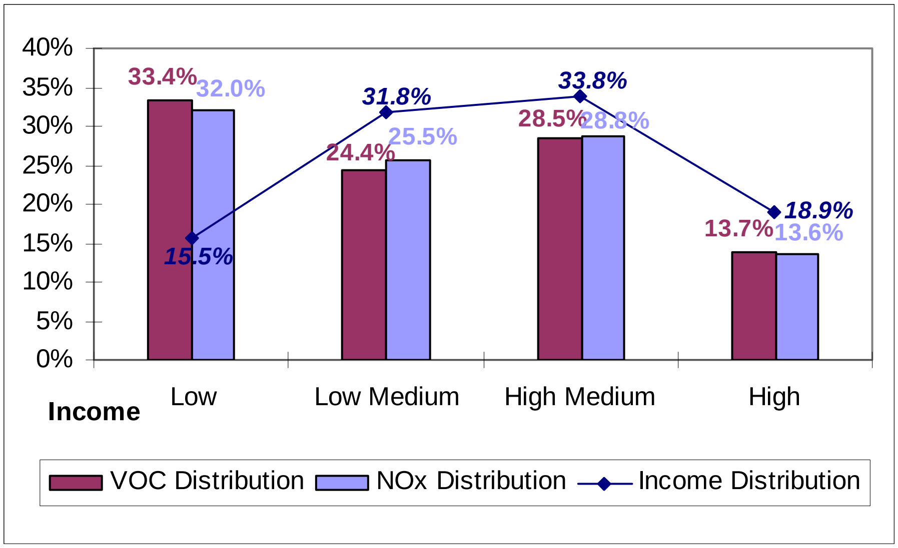

Figure 27 Income equity index of VOC and NOx emissions: Test Case 2030.

The income equity index for VOC emissions is estimated at 64.3 percent while the income equity index for NO_x emissions is 67 percent. These indexes indicate a significant decrease in the equity level [i.e., 29.4 percent (VOC emissions) and 27 percent (NOx emissions)] with reference to the Baseline. The tendency results reveal that low income groups are exposed to more than twice of emissions than they should be while low medium, high medium, and high income people are exposed to much lower levels of emissions than they should be. Households with low medium, high medium, and high income take 23.3%, 15.7%, and 27.5% lower levels of emissions than they should, respectively. It is noteworthy that households with low income (about 16 percent of total) are more likely to have disproportionately high exposure while the remaining households with medium and high income (about 84 percent of total) are more likely to be beneficiaries.

6.3.4.2. Exposure to VOC and NOx Emissions (D21)

These measures are designed to compare the coincidence or proximity of people to air pollutants such as VOC and NO_x. As a surrogate for population exposure, population density by TAZ is multiplied by the daily average emissions density, and the values are summed across the entire region. Higher human impact indexes indicate that high population density and high pollution density are more likely to occur in the same proximity (FHWA, 2004). The actual exposure is a much more complicated issue considering the complex nature of predicting hourly pollutant concentrations and population movements for exposure assessment. The averaging method (across a TAZ) used in the study, for example, will significantly underestimate local population exposures to fine particulate matter and toxic air contaminants, which are significantly elevated within 500 meters of a freeway (Guensler et al., 2004). More refined exposure models should enable this metric to be fully incorporated in the social dimension of sustainability.

Table 32 summarizes human impact indexes (HII) of VOC and NO_x emissions relative to residential population as well as employment population, for three selected scenarios. The severity of residential population exposure to VOC and NO_x emissions is estimated at 1,355 and 2,270 (HII); 468 and 319 (HII); and 4,135 and 2,767 (HII) for Baseline 2005, Mobility 2030, and Test Case 2030, respectively. Mobility 2030 significantly decreases the magnitude of human impact indexes suggesting that high population density and high pollution density are less likely to occur in the same proximity. Meanwhile, the severity of employment population exposure to VOC and NO_x emissions is estimated to 9,848 and 15,295 (HII); 3,583 and 2,200 (HII); and 3,554 and 2,300 (HII) for Baseline 2005, Mobility 2030, and Test Case 2030, respectively. The results show that high employment density and high emission density are much more likely to occur in the same proximity in most cases. Such results are consistent intuitively in that major activity centers are likely to locate adjacent to freeways and major highways (i.e., activity centers are more convenient to access than residential areas). Test Case 2030, however, indicates that high population density (not high employment density) and high emissions density are slightly more likely to occur in the same proximity.

Table 32 Human Impact Indexes

	Exposure to VOC emissions		Exposure to NO_x emissions	
	Proximity to Population	Proximity to Employment	Proximity to Population	Proximity to Employment
Baseline 2005	1,354.56	9,847.59	2,269.79	15,294.47
Mobility 2030	467.48	3,583.23	318.92	2,199.59
Test Case 2030	4,134.47	3,554.18	2,766.65	2,298.70

Figures 28 and 29 illustrate how these human impact indexes can be further used to glimpse the equity of emission concentration to population, using Baseline 2005 alternative for example. Eighty percent of VOC and NOx emissions in the region are concentrated on less than half of the total population. In other words, the remaining half of the population is exposed to only twenty percent of VOC and NO_x emissions which implies modest inequity on emission distribution over the population. Discussed earlier in the section of income equity indexes, these beneficiaries are more likely to come from higher income households than lower income households.

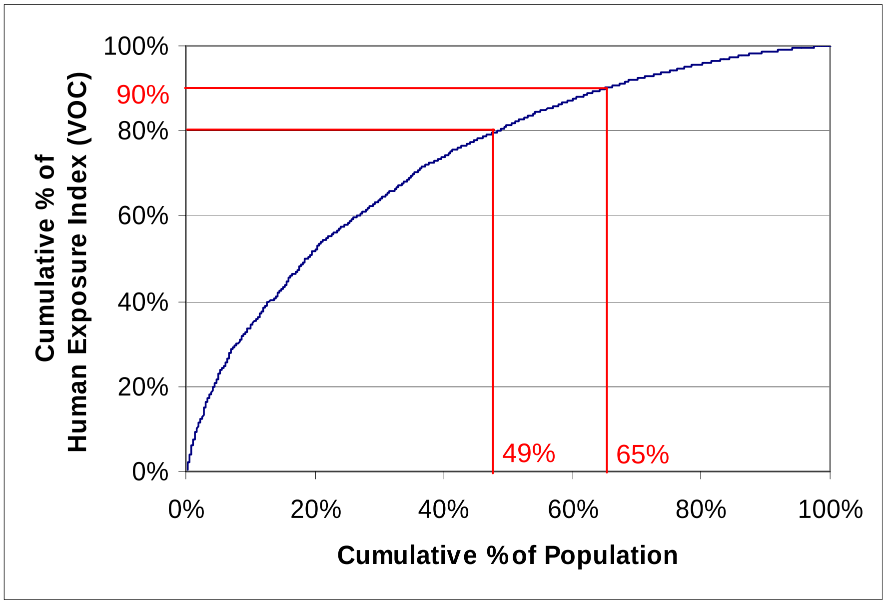

Figure 28 Human Impact Indexes of VOC Emissions: Baseline 2005.

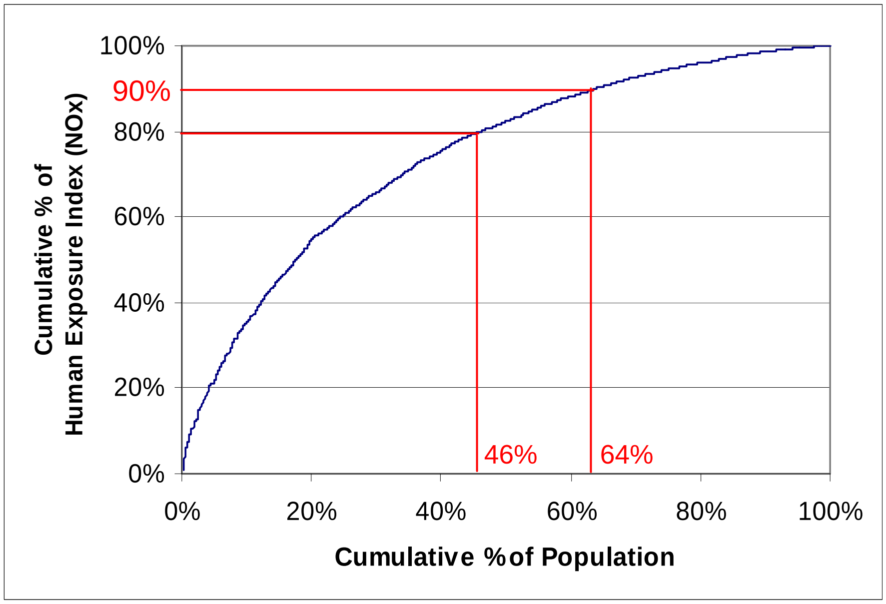

Figure 29 Human Impact Indexes of NO_x Emissions: Baseline 2005.

6.3.5. Synthesis – Individual Performance Measures

This section discusses the types of performance measures evaluated in each sustainability dimension and the evaluation results for the selected three alternatives. The evaluation results on the selected fifteen or so measures suggest that each transportation plan has some positive sustainability benefits as well as some negative impacts. These results imply that there is no absolutely superior alternative based on the evaluation of individual sustainability measures. The Baseline 2005 (the sustainability of the current transportation system) is better than the other two alternatives in terms of average freeway speed (system effectiveness), total daily CO_2 emissions (environmental integrity), daily vehicle hours traveled (economic development), and income equity indexes (social equity). The Mobility 2030 excels in vehicle miles traveled per person (system effectiveness), total daily VOC and NO_x emissions and land consumption by transportation infrastructure systems (environmental integrity), employment growth and land consumption by regional activity centers (economic development), and spatial equity indexes and human impact indexes (social equity and public health). The Test Case 2030 outpaces the sustainability of the other two scenarios in terms of vehicle miles traveled per person (system effectiveness), total daily VOC and NO_x emissions (environmental integrity), and spatial equity indexes (social equity).

Major discrepancies between the two future plans occur in the economic and social dimensions of sustainability. Mobility 2030 is a preferred plan alternative in that this plan devotes much more land area to regional economic activities than the Test Case 2030 (regional centers, retail and services, and mixed land use, for example). A sustainable transportation plan should contribute to regional economic development by enhancing regional accessibility. The Test Case 2030 plan is especially inferior to the Mobility 2030 in terms of income equity indexes and human impact indexes from a social perspective. While these plans share a common inequitable trend (i.e., lower income households are unfairly exposed to higher emissions, and higher income households are exposed to lower emissions), the Test Case 2030 introduces significant inequity in emission distribution. Similarly, Test Case 2030 indicates a severe coincidence of residential population to air pollutants based on the highest level of human impact indexes.

Now that each performance measure suggests different conclusions on the superior alternative, how does the analyst combine these inconsistent results and reach a meaningful conclusion? These results for the individual performance measures provide detailed information on sustainability, but hardly recommend a harmonized policy direction for decision makers. In order to be meaningful, these performance measures can be appropriately combined into several dimensional indexes which capture sustainability dominance and tradeoffs among the plan alternatives. The next section discusses how these individual measures can be merged into four sustainability dimensional indexes and further into a single composite sustainability index (CSI).

6.4. Sustainability Dimensional Indexes and the Composite Index

The previous section presented sustainability assessment results based on individual measures of sustainability. Such performance measures or indicators provide useful information on movement toward or away from sustainability in the various dimensions of sustainability. However, to enable the identification of dominant alternatives and the proper consideration of tradeoffs among alternatives, these measures ought to be considered simultaneously, even though their interactions are not captured in this assessment. In this context, combined sustainability indexes relative to the four sustainability dimensions provide more aggregate information while reducing information overload resulting from the individual performance measures.

An index is defined as a numerical scale used to compare variables with one another or with some reference number (Web definition for Index). Indexes are generally known to be easier to use, simple to interpret, and have the ability to reduce information overload resulting from individual performance measures (Lomax, 1997). This section identifies the procedure of combining individual measures into several indexes using a simple method of multiple criteria decision making.

To construct the sustainability indexes, this study applies for the additive utility model (or the weighted sum model) among a broad range of multiple criteria decision making methods. The additive utility model has various strengths over the other methods because it is particularly simple, it is well known, its technical parameters have a clear and explicable substantive interpretation, and it allows processing of the difficult problem of the relative importance of criteria in a precise way (Bana e Costa, 2003). The construction of composite sustainability indexes proceeds in four steps: 1) generation of the raw indicator values, 2) weighting of the normalized values, 3) normalization of the raw values, and 4) obtaining the weighted sum of normalized values for each performance measure.

The use of weights is a controversial issue because it opens up the analysis to a significant amount of subjectivity, based on value judgments on the relative importance of the different sustainability factors. On the other hand, the use of weights also allows the analyst and the decision maker to adjust weights over time as they learn which criteria are most critical. Such weighting schemes can serve as an important tool to allocate the relative importance of the various criteria in an open policy arena, effectively incorporating regional goals and priorities over time. Typically, the weights are derived through an interactive process with decision-makers, allowing the weights to be adjusted over time (Zietsman et al., 2006).

As a baseline, this study assigns equal weights to each indicator and sustainability dimension, indicating that all measures and sustainability dimensions are accorded the same relative importance. Sensitivity analyses are to be conducted on the weights to shed light on the relative overall impacts on the region of assigning various weights to the different sustainability metrics. Thus, the MCDM method can be a relatively versatile tool for assessing tradeoffs among the different sustainability dimensions in decision making to enhance sustainability.

Table 33 shows the summarized evaluation results of selected performance measures for three transportation and land use scenarios: Baseline 2005, Mobility 2030, and Test Case 2030. As the value of the criteria increases, preferences of benefit criteria, A11, C32, C33, and D12, increase in a linear and monotonic manner while preferences of the remaining cost criteria decrease in same manner. Table 34 shows the evenly distributed weights for the sustainability dimensions and performance measures as well as the normalized indicator values for each of these three scenarios.

Table 33 Selected Performance Measures and their Raw Values

Performance Measures	Unit	Baseline 2005	Mobility 2030	Test Case 2030
A11. Average freeway speed	mile/hour	47.12	42.21	42.21
A22. VMT per capita	mile/person	35.04	31.75	32.61
B11. CO_2 emissions	ton/day	72.31	110.76	110.76
B21. VOC emissions	ton/day	118.33	53.38	53.38
B23. NOx emissions	ton/day	209.64	38.33	38.33
B42. Land consumption	acre	30,513	30,216	30,968
C12. VHT per employee	minute/person	12.91	16.22	16.22
C32. Employment		2,640,069	3,319,707	3,312,122
C33. Land consumed by retail/service	acre	161,663	532,637	217,170
D12-1. Equity of VOC exposure (S)	Spatial Equity Index	19.10	23.45	23.45
D12-2. Equity of NOx exposure (S)	Spatial Equity Index	20.02	23.56	23.60
D12-3. Equity of VOC exposure (I)	Income Equity Index	93.7	87.4	64.3
D12-4. Equity of NOx exposure (I)	Income Equity Index	94.0	88.0	67.0
D21-1. Exposure to VOC emissions	Human Impact Index	1354.56	467.48	4,134.47
D21-2. Exposure to NOx emissions	Human Impact Index	2269.79	318.92	2,766.65

Table 34 Criteria Weights and Normalized Values

Sustainability Dimension (Weight)	Performance Measures	Weights	Normalized Values		
			Baseline 2005	Mobility 2030	Test Case 2030
A. System Effectiveness (0.25)	A11. Average freeway speed	0.5	1.000	0.896	0.896
	A22. VMT per capita	0.5	0.906	1.000	1.000
B. Environmental (0.25)	B11. CO_2 emissions	0.25	1.000	0.653	0.653
	B21. VOC emissions	0.25	0.451	1.000	1.000
	B23. NOx emissions	0.25	0.183	1.000	1.000
	B42. Land consumption	0.25	0.990	1.000	0.976
C. Economic (0.25)	C12. VHT per employee	0.34	1.000	0.796	0.796
	C32. Employment	0.33	0.795	1.000	0.998
	C33. Land consumed by retail/service	0.33	0.304	1.000	0.408
D. Social (0.25)	D12-1. Equity of VOC exposure (S)	0.12	0.815	1.000	1.000
	D12-2. Equity of NOx exposure (S)	0.12	0.848	0.998	1.000
	D12-3. Equity of VOC exposure (I)	0.12	1.000	0.933	0.686
	D12-4. Equity of NOx exposure (I)	0.12	1.000	0.936	0.713
	D21-1. Exposure to VOC emissions	0.26	0.345	1.000	0.113
	D21-2. Exposure to NOx emissions	0.26	0.141	1.000	0.115

Alternately, a subjective weighting scheme may utilize the attribute ranking method which essentially employs pair-wise preference judgments among attributes. The pair-wise judgment techniques help decision makers logically compare two attributes at a time for the preference and determine the relative importance (ranking) of each attribute. By assigning 1 to the most important attribute and n to the least important attribute, the rank reciprocal weights can be obtained from the following formula (Yoon and Hwang, 1995):

$$w_j = \frac{1/r_j}{\sum_{k=1}^{n} 1/r_k} \quad \text{where } r_j \text{ is the rank of the } j^{th} \text{ attribute.}$$

Normalized values for each alternative are determined by using a single-attribute utility function on linear normalized scales. The normalized ratings have a dimensionless unit, ranging from zero to one, in which the larger the rating becomes, the more preference it has (Yoon and Hwang, 1995). Finally, Table 35 calculates the utilities for the three scenarios by obtaining the weighted linear sum for each of the sustainability criteria. The formulation of the composite sustainability index using the weighted sum model (WSM) is shown below (Yoon and Hwang, 1995):

$$U_j = \sum_{k=1}^{n_k} w_k n_{kj}$$

where U_j is the utility of alternative j, w_k is the weight of the k^{th} criterion, and n_{kj} is the normalized attribute k value for alternative j.

Table 35 Dimensional and Composite Sustainability Indexes

Sustainability Indexes	Baseline2005	Mobility2030	Test Case 2030
Environmental Dimension	0.656	0.913	0.907
Social Dimension	0.566	0.984	0.467
System Effectiveness Dimension	0.953	0.948	0.948
Economic Dimension	0.703	0.931	0.734
Overall Sustainability (CSI)	**0.719**	**0.944**	**0.764**

These multidimensional sustainability indexes and the single composite indexes effectively provide aggregate information on movement toward or away from sustainability in the various dimensions. In particular, four dimensional indexes enable to investigate the tradeoffs of selecting one plan over the other plan based on the sustainability scores in each sustainability dimension. A single composite sustainability index can be also derived from aggregating these four dimensional indexes, and this index indicates the dominance among the alternatives based on the overall sustainability.

6.5. Sustainability Index as a Decision Making Tool

Both the sustainability dimensional indexes and the composite index can be directly used to compare the level of sustainability associated with plan alternatives put forward. Decision makers or analysts can effectively evaluate their plans by investigating these indexes using various visual presentations. Figure 30, for example, represents the stacked bar ranking for the integrative sustainability goal which incorporates transportation system effectiveness, environmental integrity, economic development, and social quality of life. As shown below, the Mobility 2030 achieves about 94.4% of the possible sustainability impacts achievable by the alternatives being considered, the Test Case 2030 achieves 76.4% of this value, and the Baseline alternative achieves 71.9% of this value. The two future plans, Mobility 2030 and Test Case 2030, improve overall sustainability level substantially or reasonably (respectively) compared to the baseline status. The Mobility 2030 introduces a balanced improvement on environmental integrity, economic development, and social quality of life while Test Case 2030 mainly increases environmental integrity at the expense of social quality of life.

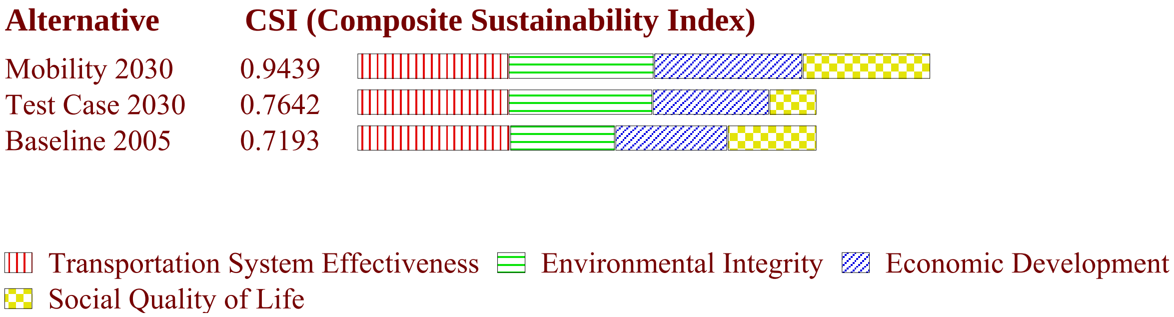

Figure 30 **Stacked Bar Ranking for Overall Sustainability Goal.**

Since major discrepancies occur at the dimensions of environmental integrity and social quality of life, Figures 31 and 32 investigate the relationships between these dimensional indexes and the composite index using a scatter diagram. Both figures highlight 1) Mobility 2030's environmental and social improvements and 2) Test Case 2030's environmental improvements versus social deterioration.

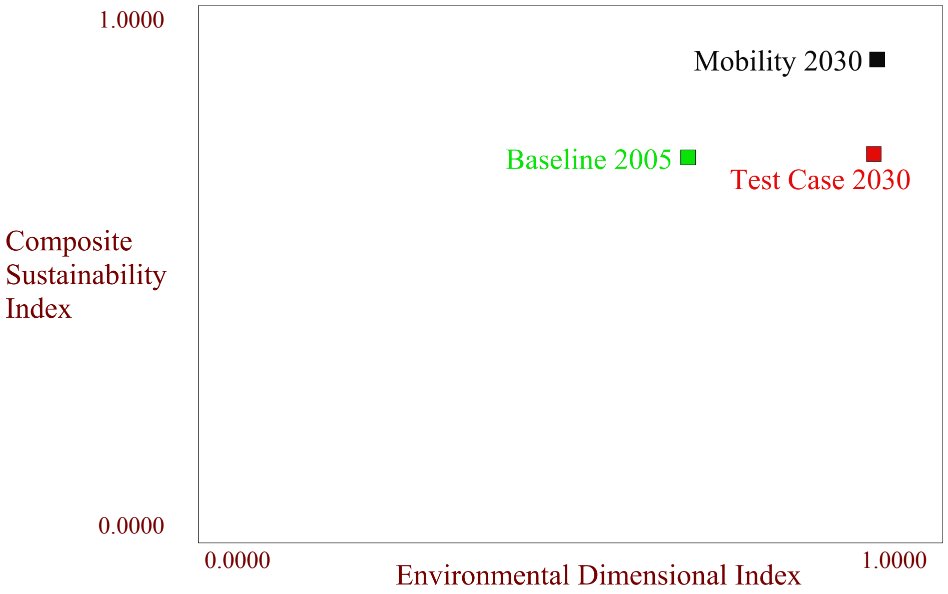

Figure 31 **Scatter Diagram for Environmental Index and CSI**

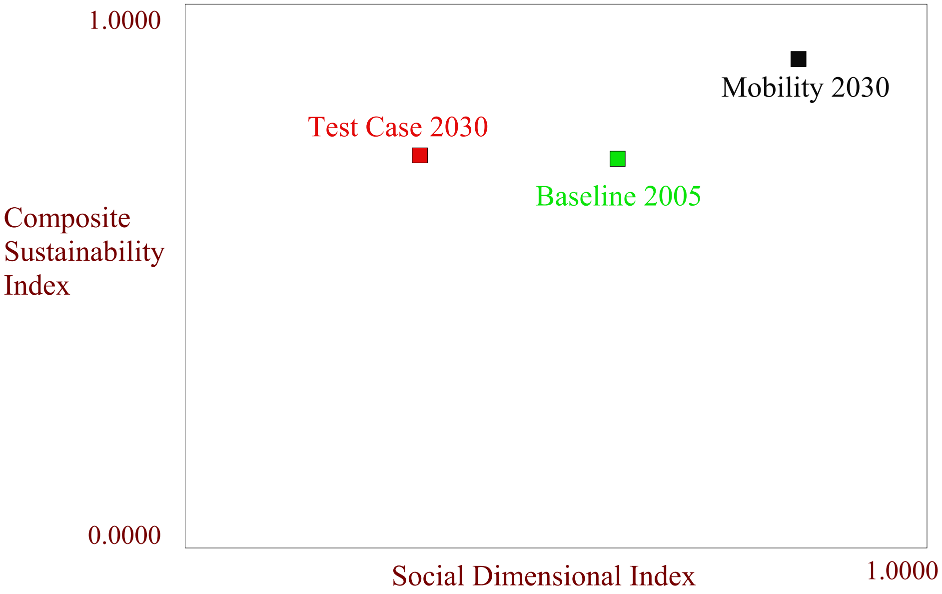

Figure 32 Scatter Diagram for Social Index and CSI

Using the four sustainability dimensional indexes for each alternative, a profile graph can be drawn to effectively capture different levels of sustainability for the scenarios evaluated, as shown in Figure 33. While a “full” diamond shape (shown as the largest parallelogram in the figure) is considered to be the maximum achievable level of sustainability for these scenarios put forward, the area of each diamond conveys the relative level of sustainability of the competing alternatives. The diamond covered with a dashed line represents the sustainability of the Baseline 2005, the diamond filled with dots represents the sustainability of the Test Case 2030, and the solid diamond represents the sustainability of the Mobility 2030. Clearly, the Mobility 2030 appears to be the “best” of the three alternatives since the plan results in the highest value of composite sustainability index: 94.4 percent. The four sustainability dimensional indexes, however, provide additional information on the achievement of each alternative in terms of each sustainability perspective. These dimensional indexes show that while the three alternatives seem to be comparable from a system effectiveness perspective, the main disparities are to be found in their environmental, social, and economic sustainability impacts. The investigation of these multiple dimensional indexes using the visualizing tool enables the decision maker to discover the tradeoffs between non-identical alternatives. While the Mobility 2030 is a near-dominant alternative, some tradeoffs occur when comparing the Baseline and Test Case alternatives. The Test Case 2030 is a superior alternative from an environmental standpoint while the Baseline 2005 is a superior alternative for advancing social equity and public health. Considering that these two alternatives result in a comparable level of overall sustainability, the Baseline 2005 is a more equitable and healthier plan while the Test Case 2030 is a more environment-friendly plan. Thus, in moving from the 2005 Baseline scenario to the "Test Case" scenario, the overall gains made in system-wide sustainability, come from increases in environmental sustainability at the expense of social equity and public health.

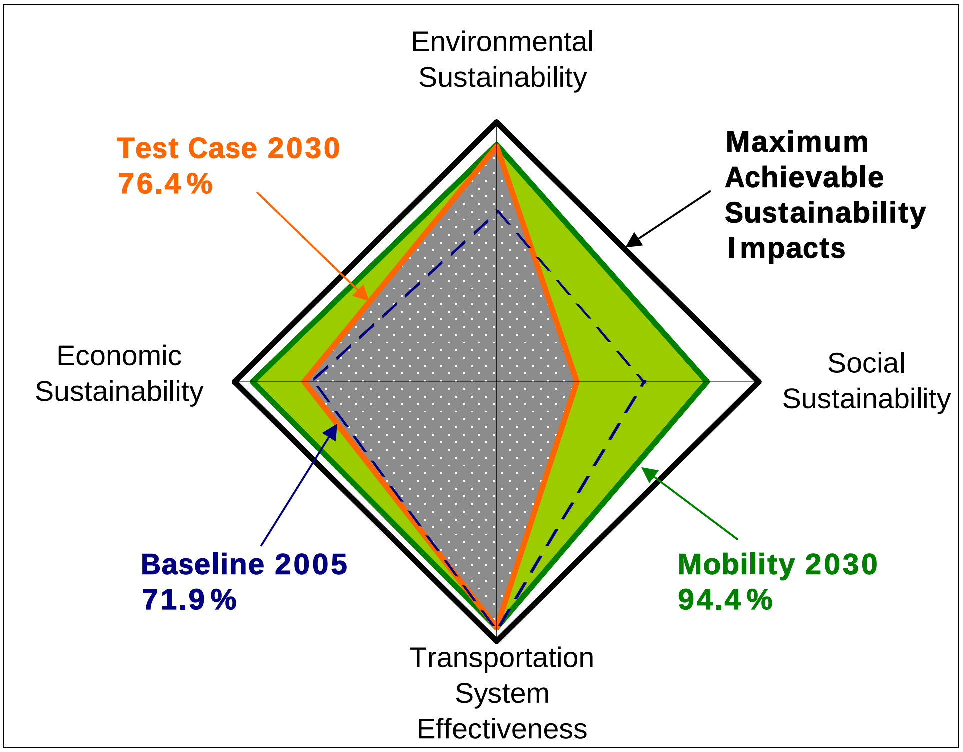

Figure 33 Decision support tool visualizing sustainability indexes

Understanding these types of tradeoffs can be valuable for understanding the impacts of decision making on the region's ability to achieve its current priorities. In cases where the overall sustainability score is negligible between two or more different scenarios, but there are definite differences in the scores of the four different sustainability dimensions, understanding the impacts of selecting one plan over another would entail understanding the tradeoffs that are being made from plan to plan. Therefore, the dimensional sustainability indexes as well as the composite index can function as decision criteria to identify superior plans for predetermined objectives and priorities. These priorities, determined from subjective weights, are critical for deciding the relative emphasis to be placed on each dimension of sustainability. These nuances suggest that decision makers should not just rely on a resulting index but must also examine the relevance of (1) weights and (2) evaluating process relative to the vision, goals, and priorities for their respective regions (Jeon et al., 2007).

The evaluation above is based on all evenly distributed weights for each performance measure and sustainability dimension indicating that equal levels of importance are placed on all measures and dimensions. As a baseline, such a "neutral" weighting scenario enables decision makers to readily track the changes in the results by applying different weights. These weights essentially indicate the relative importance and regional priorities that the decision maker accords to the different sustainability dimensions and measures. Sensitivity analyses on different regional priorities are discussed in the following chapter.

CHAPTER 7

SENSITIVITY ANALYSIS

Multiple criteria decision making (MCDM) methods commonly employ a weighting system that assigns weight on each criterion based on its relative importance in order to consider multiple criteria at the same time. While the use of a weighting system is controversial due to its subjective nature, weights can also serve as an important tool to allocate the relative importance of the various criteria in an open policy arena, effectively incorporating regional goals and priorities. In the previous chapter, this study uses a neutral weighting system that assigns evenly distributed weights on each performance measure and sustainability dimension (i.e., equal levels of importance are placed on all dimensions and measures). This chapter demonstrates an extensive sensitivity analysis on these weights to enable decision makers to take into consideration a variety of "what if" situations. These sensitivity analyses will provide practitioners with the alternative they are most likely to select if they weight the different dimensions and measures in various ways while indicating tipping points or switchover points of the composite sustainability index from one alternative to another. The intent is to shed light on which alternative best achieves different regional priorities and goals.

7.1. Sensitivity Analysis: Weights on Sustainability Dimensions

For further sensitivity analysis, the previously used neutral weighting system is being considered as a base scenario. Under the base scenario, the Mobility 2030 is the superior alternative by achieving 94.4% of the possible sustainability impacts achievable by all the alternatives being considered. The Baseline 2005 and the Test Case 2030 alternatives are rather comparable, achieving 71.9% and 76.4% of this value, respectively. This section mainly investigates the possibility of switchover in these results on the best alternative as a function of the weighting of the different sustainability dimensions. Weights changes on the individual performance measures are not considered in this section, so equal levels of importance are assigned for the measures included in each sustainability dimension. Figure 34 represents how changing weights on sustainability dimensions influences the composite sustainability indexes (CSI) of three alternatives, sorted by ascending order of the Mobility 2030's CSI. The Mobility 2030 is still the dominant alternative in most cases when all possible combinations of weights on the four sustainability dimensions are considered.

Figure 34 CSI Value Changes over Weights on Sustainability Dimensions

The Baseline 2005 slightly outpaces the Mobility 2030 alternative under the only exception out of thousands of possible cases when decision makers in a region end up with assigning 100% of weight solely on the transportation system effectiveness goal.

While the Test Case 2030 and Baseline 2005 scenarios are more sensitive depending on varied weights, Mobility 2030 produces relatively consistent CSI values with maintaining its dominance over the other two plans regardless of varied weights. Thus, the previous conclusion that Mobility 2030 is a superior alternative remains relevant not only under the neutral weighting system but also under all possible combination of weights. The vertical line represents the baseline scenario with the neutral weighting system.

Further analysis is conducted in order to investigate how changing weights on each sustainability dimension affects the overall sustainability level of three alternatives. The following four figures illustrate the range of the composite sustainability indexes of the three alternatives with changes in the weights of each sustainability dimension. Figures 35 through 38 show the sensitivity graphs for the each sustainability dimension of environmental integrity, social quality of life, transportation system effectiveness, and economic development. Compared to the sensitivity of the other dimensions, the weight on the social quality of life results in a much wider range for the composite sustainability indexes regarding three alternatives although the Mobility 2030 remains the superior alternative throughout all the sensitivity scenarios.

As shown in Figure 35, increasing the weight on the environment dimension mainly affects the composite sustainability indexes of the Test Case 2030 and the Baseline 2005 alternatives: the Baseline 2005 is outpaced by the Test Case 2030 when the analyst weighs more than 24 percent on the environment. The overall sustainability of Mobility 2030 alternative is insensitive to the weight changes in the environment dimension, maintaining its dominance over the other alternatives. Figure 36 shows that increasing the weight on the dimension of social quality of life causes a significant decrease in the composite sustainability indexes of all three alternatives. Especially, the Test Case 2030 alternative decreases in the index value from the highest value of 0.859 to the lowest value of 0.306. While the Mobility 2030 does not release its dominance over the other two alternatives, the Test Case 2030 is outpaced by the Baseline 2005 if decision makers assign more than 29 percent of weight on the social quality of life.

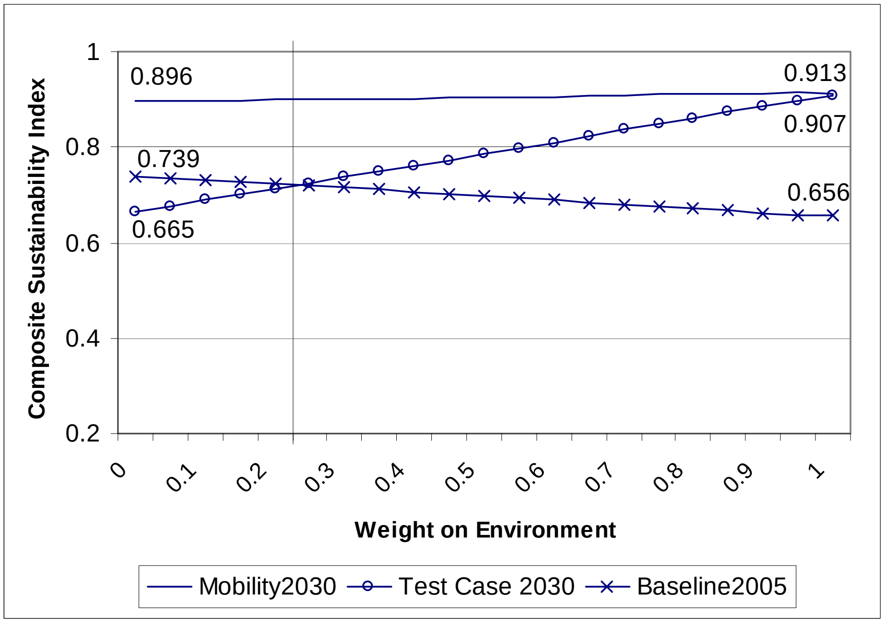

Figure 35 Sensitivity Graph for Environmental Integrity.

Figure 36 Sensitivity Graph for Social Quality of Life.

Figure 37 shows that increasing the weight on the dimension of transportation system effectiveness causes a moderate increase in the composite sustainability indexes of all three alternatives. The Baseline 2005 and Test Case 2030 alternatives increase in the index values in a comparable pattern; however, the Baseline 2005 slightly surpasses the Mobility and the Test Case 2030 alternatives if analysts assign 97 percent and more weight solely on transportation system effectiveness. Figure 38 shows that increasing the weight on the economy dimension causes a slight change in the composite sustainability indexes of all three alternatives. While the Mobility 2030 alternative maintains its dominance regardless of weights, the Baseline 2005 is slightly surpassed by the Test Case 2030 alternative if decision makers assign 13 percent or more weight on the economic dimension of sustainability.

In summary, the Mobility 2030 is the single “dominant” alternative at any time even when decision makers change their preferences on each sustainability dimension. There exist very few exceptions that the Mobility 2030 is surpassed by other alternatives. The Mobility 2030 only becomes comparable or a slightly inferior alternative to the Test Case 2030 and the Baseline 2005 alternatives when transportation system effectiveness is the only interest of policy makers. In other words, the Mobility 2030 is considered a superior plan when decision makers evaluate these plans based on not only system effectiveness perspective but also environmental, economic, and social perspectives. Considering broader impacts of transportation system planning is consistent with the main theme of sustainability-oriented planning and evaluation. Therefore, the Mobility 2030 is considered not only a superior alternative but also a more sustainable alternative.

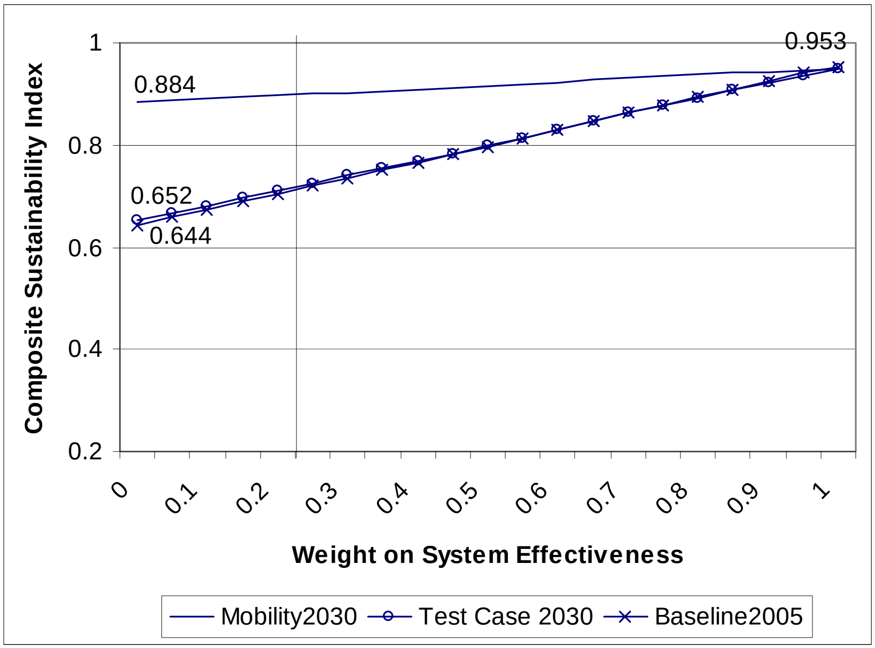

Figure 37 Sensitivity Graph for Transportation System Effectiveness.

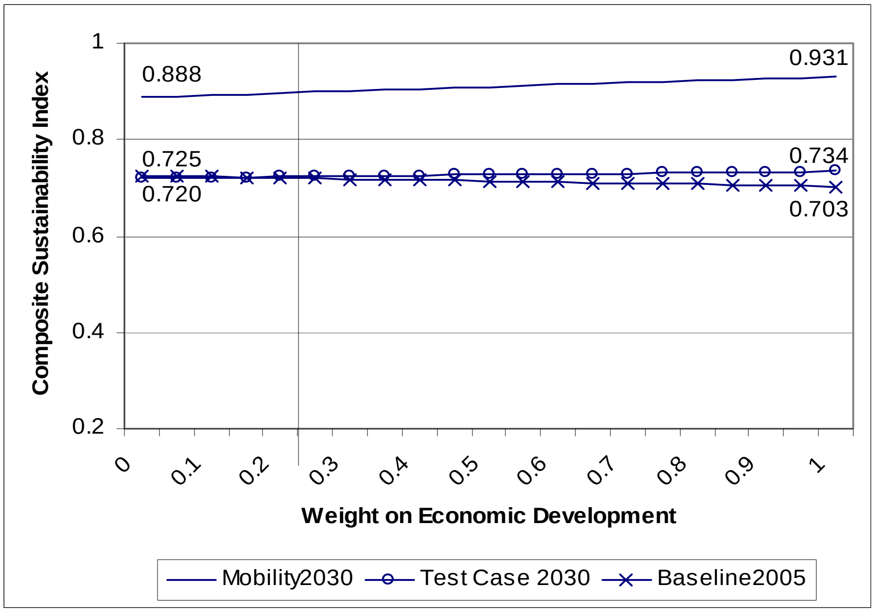

Figure 38 Sensitivity Graph for Economic Development.

7.2. Sensitivity Analysis: Weights on Dimensional Performance Measures

The previous section concludes that the Mobility 2030 is the preferred plan regardless of weight changes in four sustainability dimensions. This section investigates if this conclusion remains valid with weight changes in individual performance measures included in the sustainability dimensions. This section also discusses the possibility of switchover in these results on the best alternative and the implications of such switchover, if any. Further analysis is conducted in order to explore how changing weights on individual performance measures affects the overall sustainability level of the three alternatives.

7.2.1. Performance Measures in Transportation System Effectiveness

Average congested freeway speed and vehicle miles traveled (VMT) per capita are two performance measures selected to capture transportation system effectiveness. Figures 39 and 40 illustrate the range of the composite sustainability indexes of the three alternatives with changes in weights of these two measures: average congested freeway speed and VMT per capita. In each figure, the vertical line over the graphs represents the baseline scenario with the neutral weighting system, with equal importance placed on average freeway speed and vehicle traveled miles (i.e., 12.5 percent) assuming that the dimension of system effectiveness occupies 25 percent of importance in the overall decision.

Figure 39 implies that the Mobility 2030 alternative remains the best unless decision makers assign more than 70 percent weight on the single measure of average freeway speed. Similarly, Figure 40 indicates that the Mobility 2030 is still the preferred alternative regardless of the weights assigned on vehicle miles traveled per person. In summary, changing the weights on performance measures in the dimension of transportation system effectiveness mainly influences the composite sustainability indexes of Baseline 2005 and Test Case 2030 alternatives. While the Baseline 2005 may outpace the Mobility 2030 alternative in some extreme cases, the Mobility 2030 is still the dominant alternative in most cases with weight changes on these two performance measures.

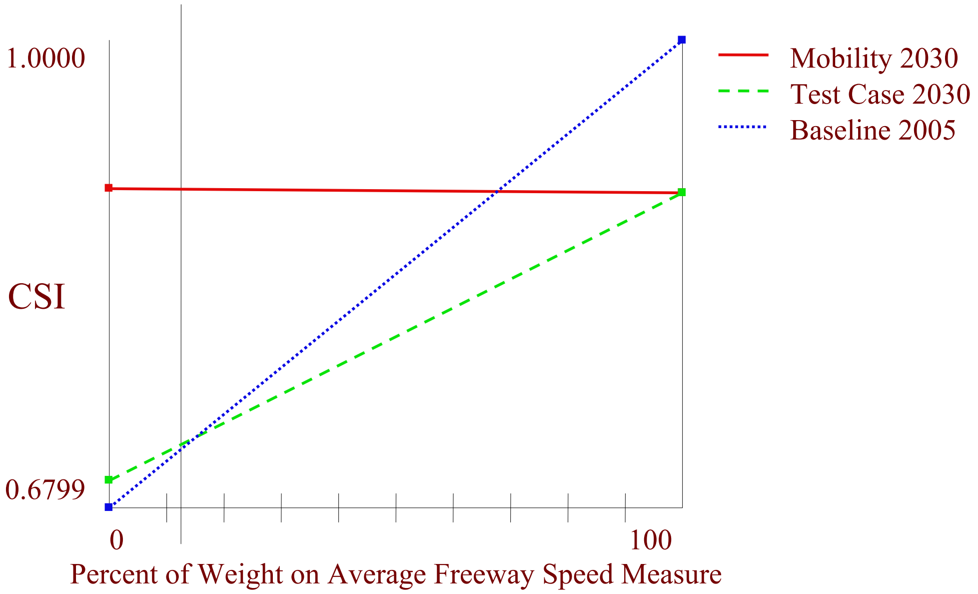

Figure 39 Sensitivity Graph for Average Freeway Speed

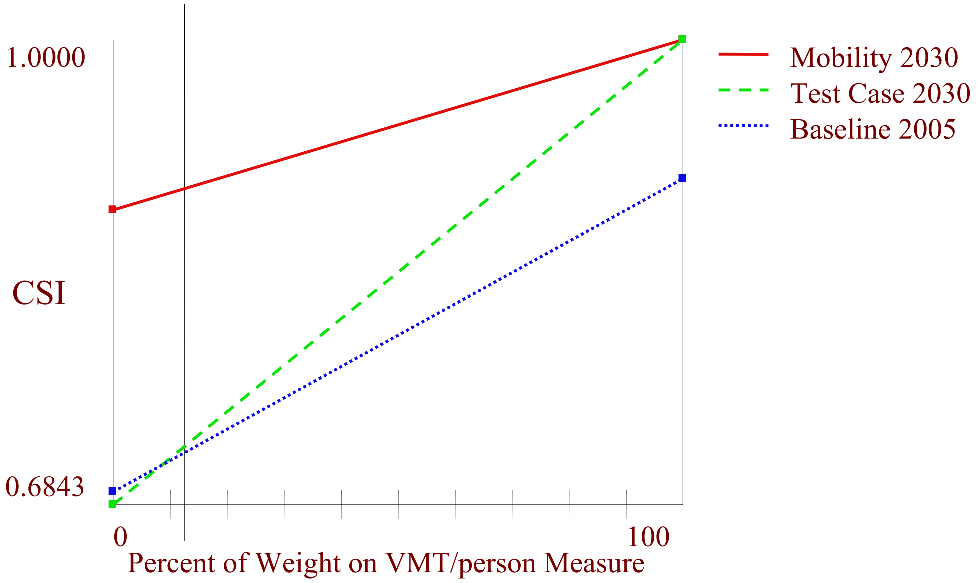

Figure 40 Sensitivity Graph for Vehicle Miles Traveled Per Capita

7.2.2. Performance Measures in Environmental Dimension

Total daily emissions of carbon dioxides (CO_2), volatile organic compounds (VOC), and oxides of nitrogen (NO_x), and land consumption by transportation infrastructure systems are four performance measures selected to capture the environmental dimension of sustainability. Figures 41 through 44 illustrate the range of the composite sustainability indexes of the three alternatives with changes in weights of these four measures: total daily emissions of CO_2, VOC, and NO_x, and land consumption by transportation systems. In each figure, the vertical line over the graphs represents the baseline scenario with the neutral weighting system, with equal importance placed on the four measures (i.e., 6.25 percent) assuming that the environmental dimension occupies 25 percent of importance in the overall decision.

Figure 41 indicates that the Mobility 2030 is outpaced by Baseline 2005 alternative if decision makers assign more than 40 percent of weight on CO_2 emissions. On the other hand, Figures 42 through 44 indicate that Mobility 2030 is still the dominant alternative no matter what preferences decision makers hold on VOC and NO_x emissions and land consumption measures.

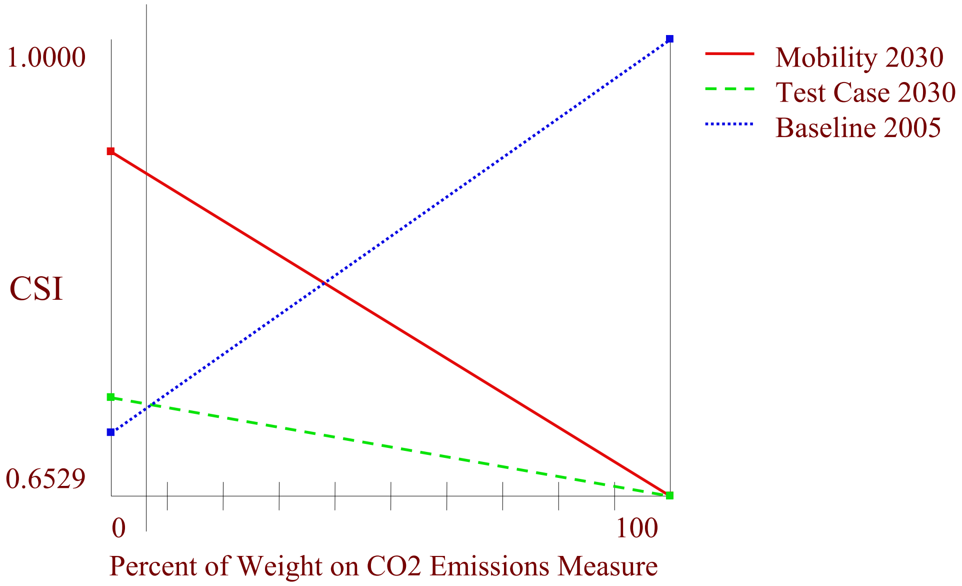

Figure 41 Sensitivity Graph for CO_2 Emissions.

Thus, changing the weights on performance measures of the environmental dimension will not influence final decision on the preferred alternative except the case where the CO_2 emissions measure holds 40 percent or more importance in decision making. Weight changes on VOC emissions, NO_x emissions, and land consumption measures will not change the previous conclusion that Mobility 2030 is the most preferred alternative.

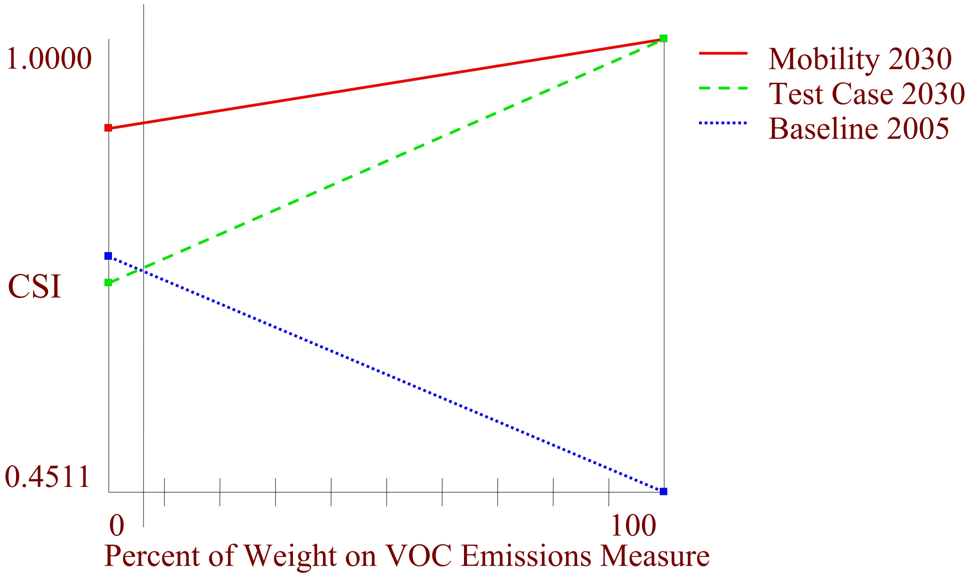

Figure 42 Sensitivity Graph for VOC Emissions.

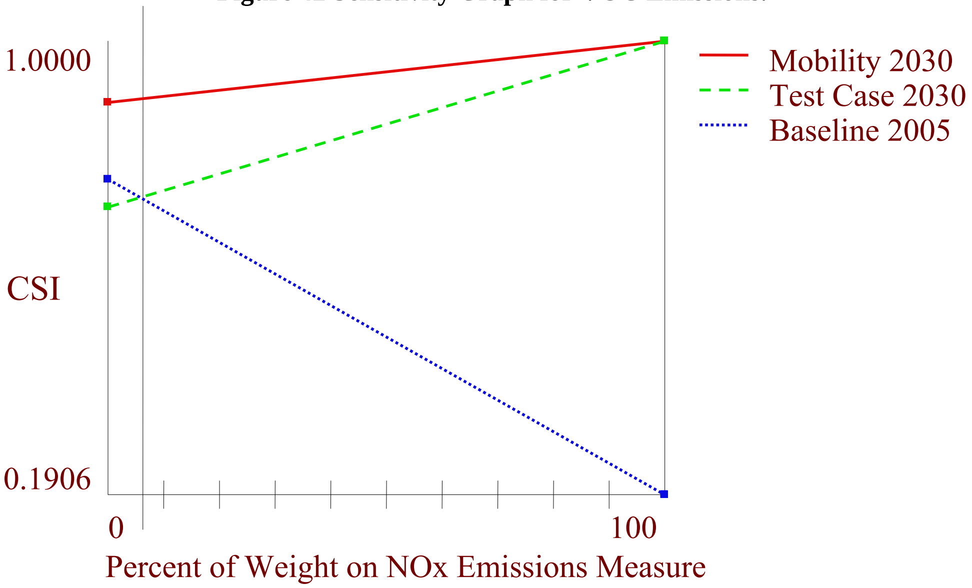

Figure 43 Sensitivity Graph for NOx Emissions.

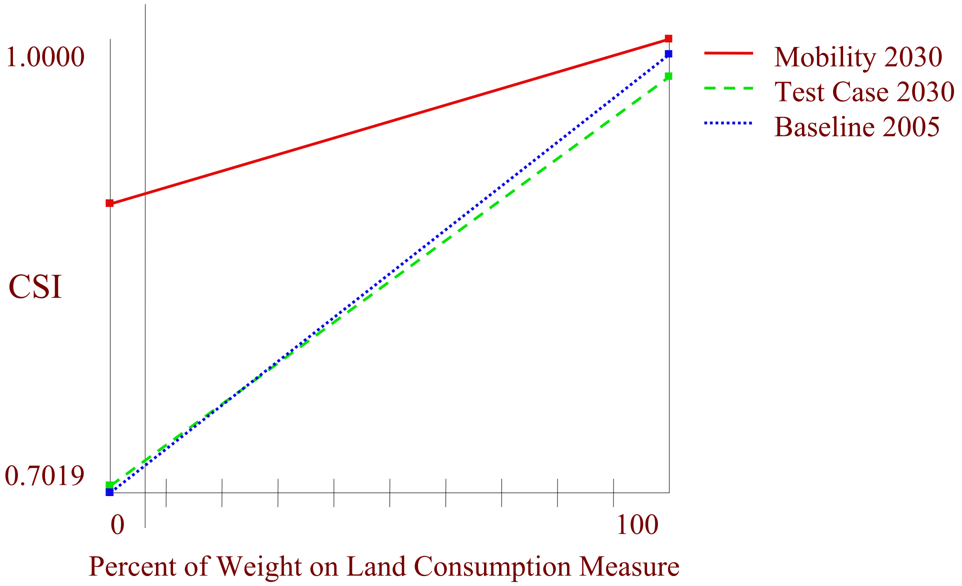

Figure 44 Sensitivity Graph for Land Consumption by Transportation System.

7.2.3. Performance Measures in Economic Dimension

Vehicle hours traveled (VHT) per employee, employment, and land consumption by retail and service are three performance measures selected to capture the economic dimension of sustainability. Figures 45 through 47 illustrate the range of the composite sustainability indexes of the three alternatives with changes in weights of these three measures: VHT per employee, employment, and land consumption by business purpose. In each figure, the vertical line over the graphs represents the baseline scenario with the neutral weighting system, with equal importance placed on the three measures (i.e., 8.33 percent) assuming that the economic dimension occupies 25 percent of importance in the overall decision.

Figure 45 indicates that the Mobility 2030 is outpaced by Baseline 2005 alternative if decision makers assign more than 50 percent weight on the single measure of vehicle hours traveled per employment. On the other hand, Figures 46 and 47 show that the Mobility 2030 is still the dominant alternative no matter the preference of decision makers on measures of employment and land consumption by retail and service. Thus, vehicle hours traveled per employment is the only measure in the economic dimension whose relative importance may bring out the conclusion that the Baseline 2005 preferred over the Mobility 2030 alternative.

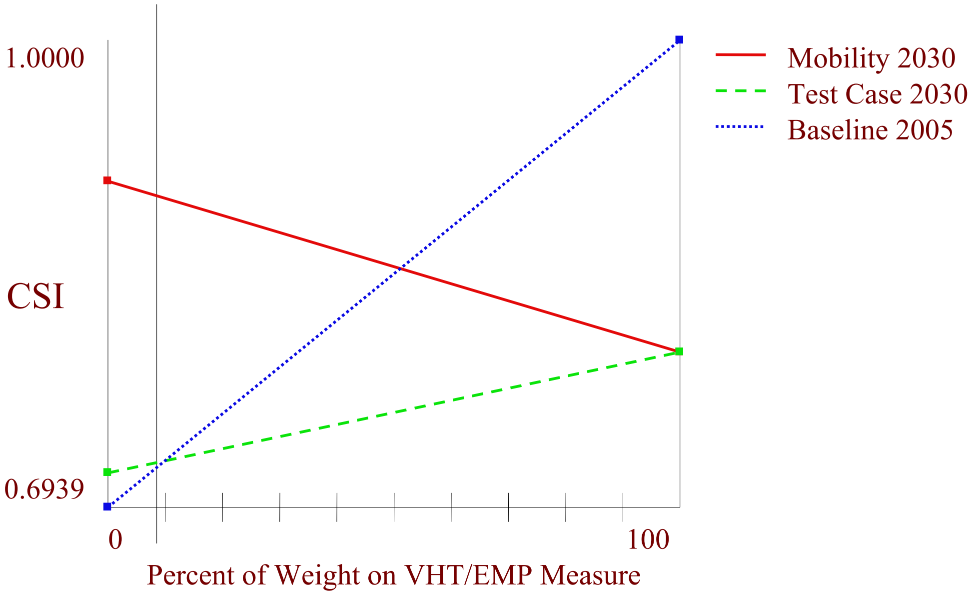

Figure 45 Sensitivity Graph for Vehicle Hours Traveled per Employment.

Figure 46 Sensitivity Graph for Employment.

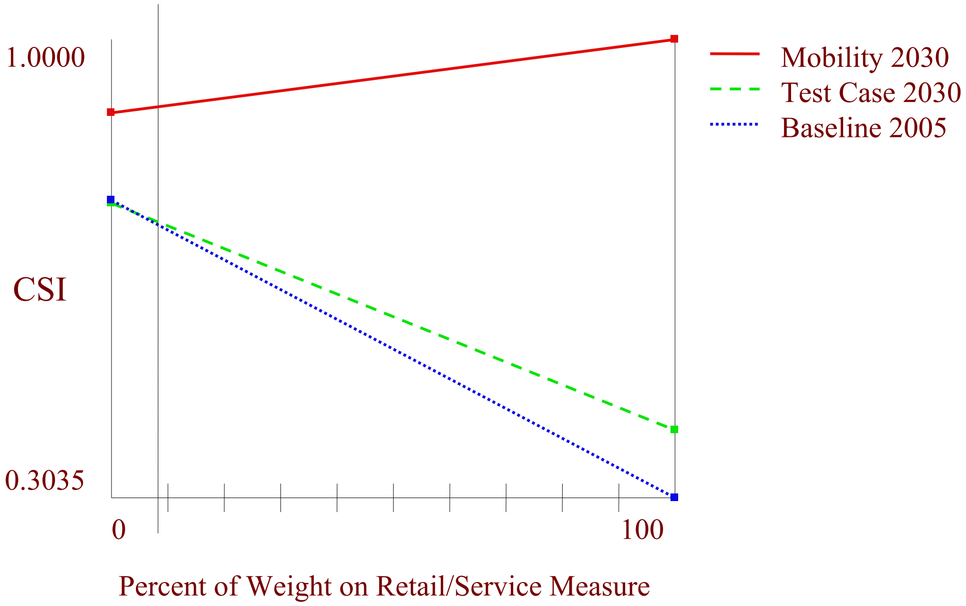

Figure 47 Sensitivity Graph for Land Consumption by Retail and Service.

7.2.4. Performance Measures in Social Dimension

Improving social equity and public health are two major goals considered in the social dimension of sustainability. Spatial and income equity of exposure to VOC and NO_x emissions are selected as equity-related measures while human exposure to VOC and NO_x emissions are selected as public health related measures. Figures 48 through 53 illustrate the range of the composite sustainability indexes of the three alternatives with changes in the weights on these measures: spatial and income equity of exposure to VOC and NO_x emissions and human exposure to these emissions. In each figure, the vertical line over the graphs represents the baseline scenario with the neutral weighting system, with equal importance on equity and public health goals (i.e., 12.5 percent) assuming that the social dimension occupies 25 percent of importance in the overall decision.

Figures 48 and 49 show that changing the weights on “spatial” equity of exposure to VOC and NO_x emissions will not change the previous conclusion that the Mobility 2030 is the preferred alternative. On the other hand, “income” equity indexes of exposure to VOC and NO_x emissions are the most noticeable measures that may change the previous conclusion that the Mobility 2030 is the preferred alternative. As shown as Figures 50 and 51, the Baseline 2005 should be selected as the best alternative whenever decision makers determine to assign 20 percent or more weight on income equity measures.

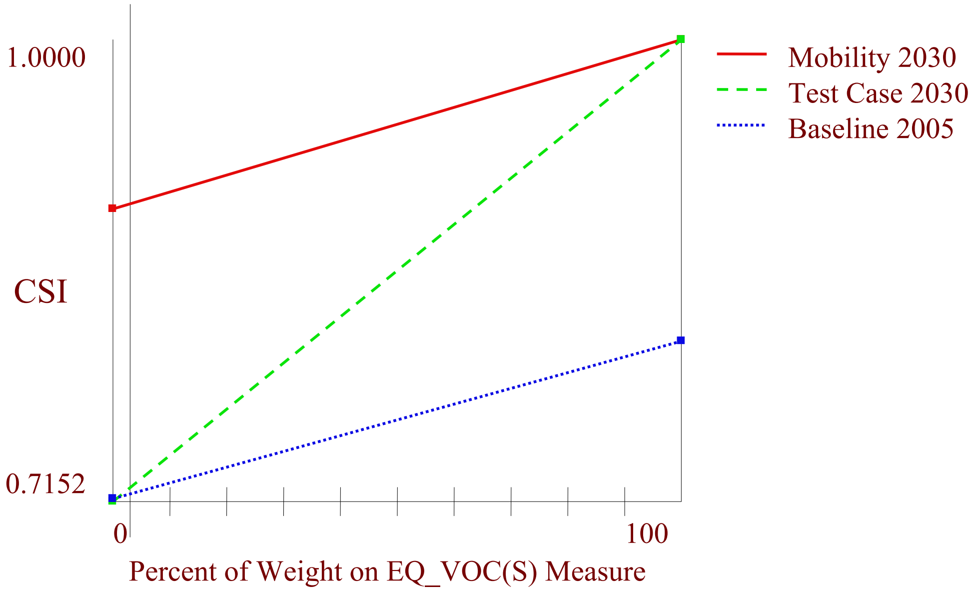

Figure 48 Sensitivity Graph for Spatial Equity of VOC Exposure.

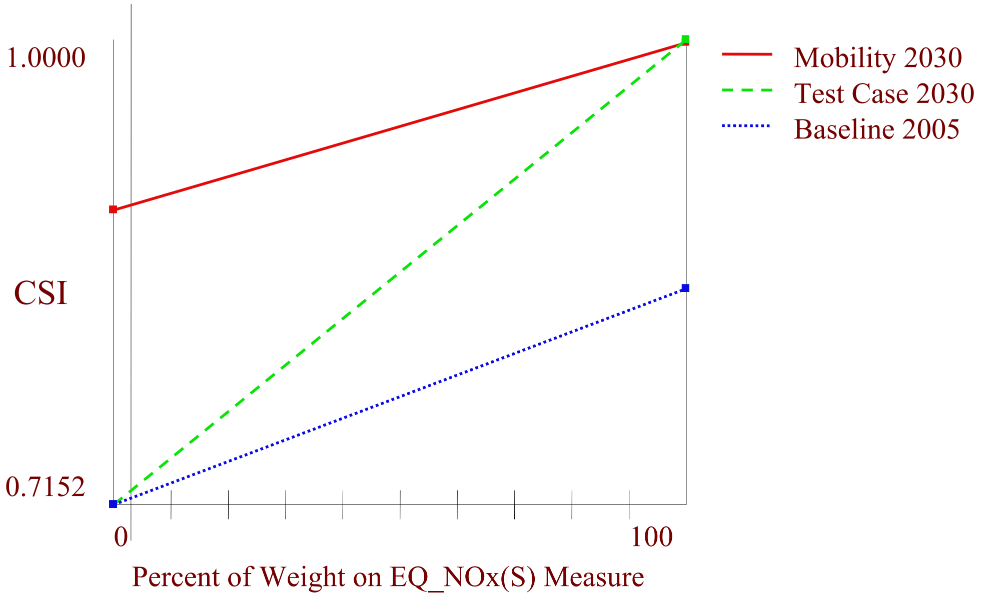

Figure 49 Sensitivity Graph for Spatial Equity of NO_x Exposure.

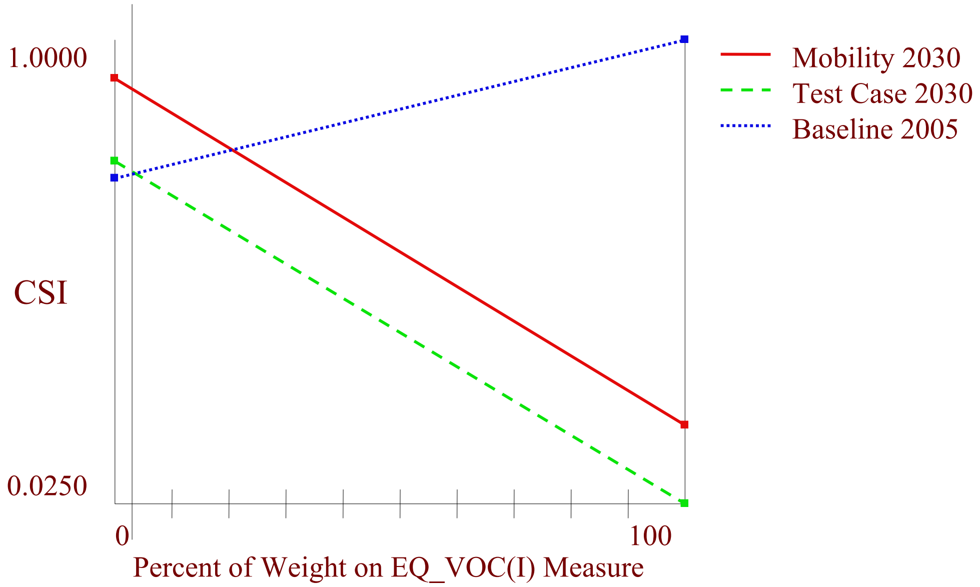

Figure 50 Sensitivity Graph for Income Equity of VOC Exposure.

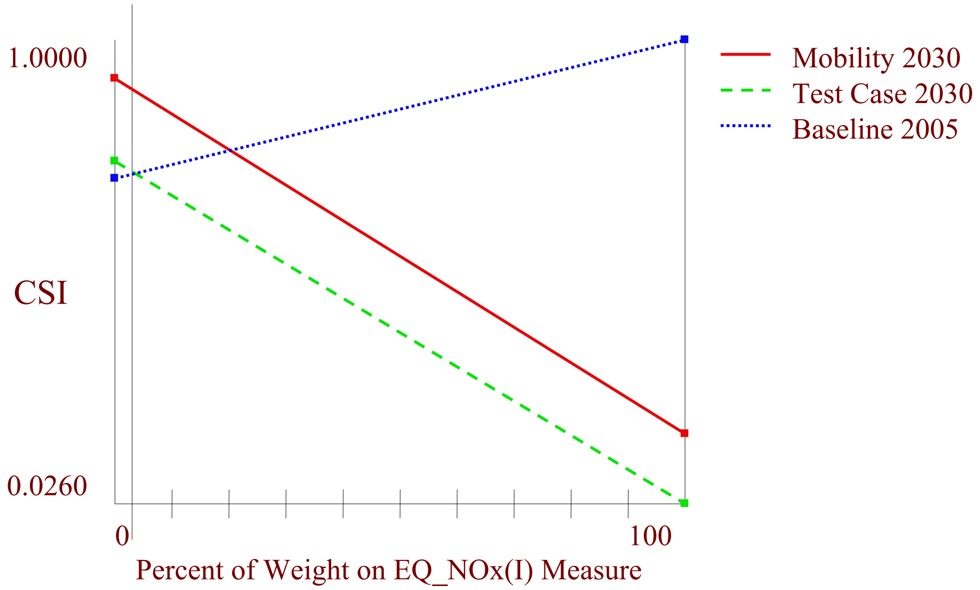

Figure 51 Sensitivity Graph for Income Equity of NOx Exposure.

Figures 52 and 53 again conclude that the Mobility 2030 is still the dominant alternative regardless of weight changes on the human exposure measures. Thus, the Baseline 2005 may be considered to be more sustainable than the Mobility 2030 if a particular region has a priority on the equity of emission distribution to different income group people.

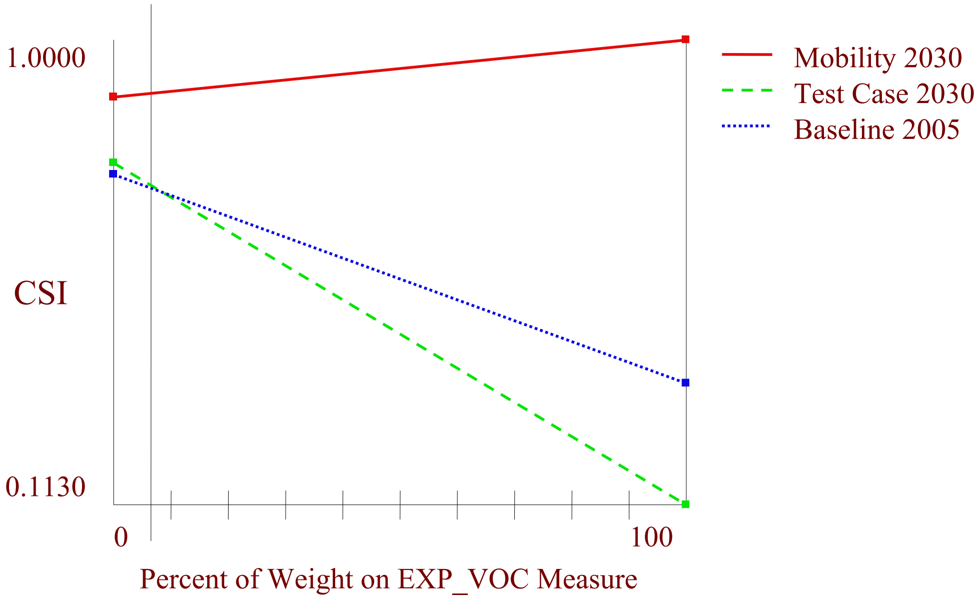

Figure 52 Sensitivity Graph for Human Exposure to VOC Emissions.

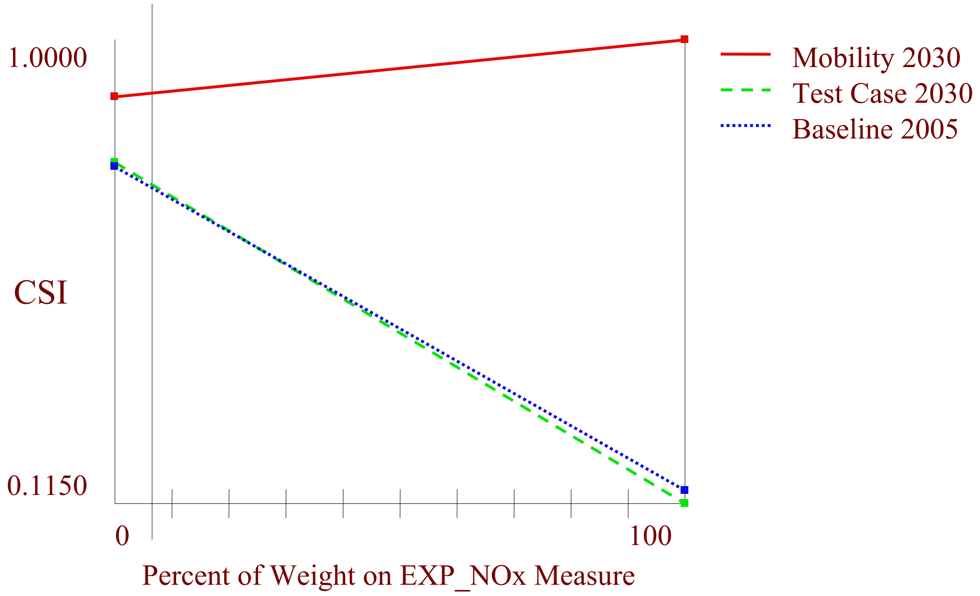

Figure 53 Sensitivity Graph for Human Exposure to NOx Emissions.

7.3. Findings and Implications on Sensitivity Analysis

This section conducts the extensive sensitivity analysis on the weights of sustainability dimensions as well as dimensional performance measures to find out how sensitive the composite sustainability indexes of the selected alternatives are to the sustainability dimensions and performance measures. Based on the neutral weighting system, the Mobility 2030 is a preferred alternative with 0.94 of composite index, followed by the Test Case 2030 and the Baseline 2005 alternatives with 0.76 and 0.72 of composite indexes, respectively. The sensitivity analysis is conducted with respect to the base weighting scenario that assigns all evenly distributed weights on each sustainability dimension and performance measure.

Results on the sensitivity analysis indicate that the Mobility 2030 is a mostly dominant alternative throughout all the possibilities of weighting schemes for sustainability dimensions and performance measures. In case of weight changes on the four sustainability dimensions (assuming that weights on performance measures are fixed at neutral), the Mobility 2030 is the single dominant alternative with very few exceptions. The Mobility 2030 only becomes comparable or slightly inferior to the Test Case 2030 and the Baseline 2005 alternatives when decision makers end up with assigning 100 percent weight solely on the transportation system effectiveness goal. In other words, Baseline 2005 may be considered to be a superior alternative only if a particular region has an absolute priority on system effectiveness while not being interested in environmental, economic, and social impacts. This situation, however, is very unlikely to happen since sustainability-oriented planning and evaluation should take into consideration much broader impacts of transportation systems on economy, environment, and society. Thus, Mobility 2030 is not only a superior plan but also a more sustainable plan because this alternative is preferred when economic, environmental, and social perspectives of sustainability are incorporated into evaluation process.

In case of weight changes on the individual performance measures, there exist a couple of exceptions that the Mobility 2030 is outpaced by the Baseline 2005 alternative. Average freeway speed, total daily CO_2 emissions, vehicle hours traveled per employment, and income equity measures of exposure to VOC and NO_x emissions are such performance measures whose weighting scheme may change the previous conclusion. The sensitivity analysis graphs indicate tipping points or switchover points of the highest composite sustainability indexes from one alternative (the Mobility 2030) to another (the Baseline 2005). The Baseline 2005 would be a preferred alternative instead of the Mobility 2030 whenever decision makers assign more than 1) 70 percent weight on the average freeway speed measure, 2) 40 percent weight on the CO_2 emissions measure, 3) 50 percent weight on vehicle hours traveled per employment, or 4) 20 percent weight on income equity measures of air pollutants. Still, the Mobility 2030 remains the preferred alternative regardless of possible weighting schemes on the remaining performance measures.

Considering that the fact regional priorities on sustainability are woven into the weighting scheme, decision makers should conduct such a sensitivity analysis on the weights which are often non-deterministic and subjective. The sensitivity analysis conducted in the study suggests that regional priorities or weights also play a critical role on deciding the preferred plan alternative. Thus, the alternatives that surface as superior are considered superior from the standpoint of what is considered important with respect to the regional priorities. In other words, the sustainability evaluation results may be different depending on weights or priorities of the different sustainability dimensions/measures as determined based on the regional sustainability vision and goals (Jeon et al., 2007).

What this means is that, as decision makers may place more emphasis on different criteria of the evaluation, this exercise may result in the selection of different plans. The sensitivity analysis essentially reveals the switch-over points for identifying different alternatives as "best." Thus, by comparing these sensitivity analysis scenarios to the "neutral" scenario where all weights are assumed to be equal, the analyst can shed light on the actual expected outcomes of assigning different weights by explaining the sustainability contributions of the resulting alternative. Using the switchover information, the analyst can also provide adequate decision support information to decision makers by letting them know when the relative importance they have given to a particular criterion will result in a switch from one alternative to another. Hence, if the subjective weightings of decision makers tip the neutral weightings alternative in favor of another alternative, the analyst can be prepared to explain what could be expected from a sustainability impacts viewpoint by selecting that scenario.

Furthermore, such sensitivity analysis exercises enable decision makers to confront uncertainties commonly associated with the decision making process. Decision makers can proactively overcome these uncertainties by pre-examining the expected outcomes of different weight assignments and by identifying the level of uncertainties inherent in a particular decision. The proposed decision support tool in the previous chapter can effectively capture such uncertainties resulting from the subjective weighting schemes. Compared to the sustainability outcomes depending on the "neutral" weighting scheme in Figure 33, Figure 54 represents the expected outcome regarding the "least favorable" weighting scenarios. Such weighting scenarios result in the lowest possible level of sustainability contributions on each sustainability dimension for each plan alternative. The Mobility 2030 achieves about 64% of the possible sustainability impacts achievable by the alternatives being considered, the Test Case 2030 achieves 50.1% of this value, and the Baseline 2005 achieves 39.4% of this value. The composite sustainability indexes decrease approximately by 30 percent in Mobility and Test Case 2030 alternatives and 45 percent in Baseline 2005. On the other hand, the largest parallelogram conveys the greatest estimate of what can be expected depending on the "most favorable" weighting scenarios.

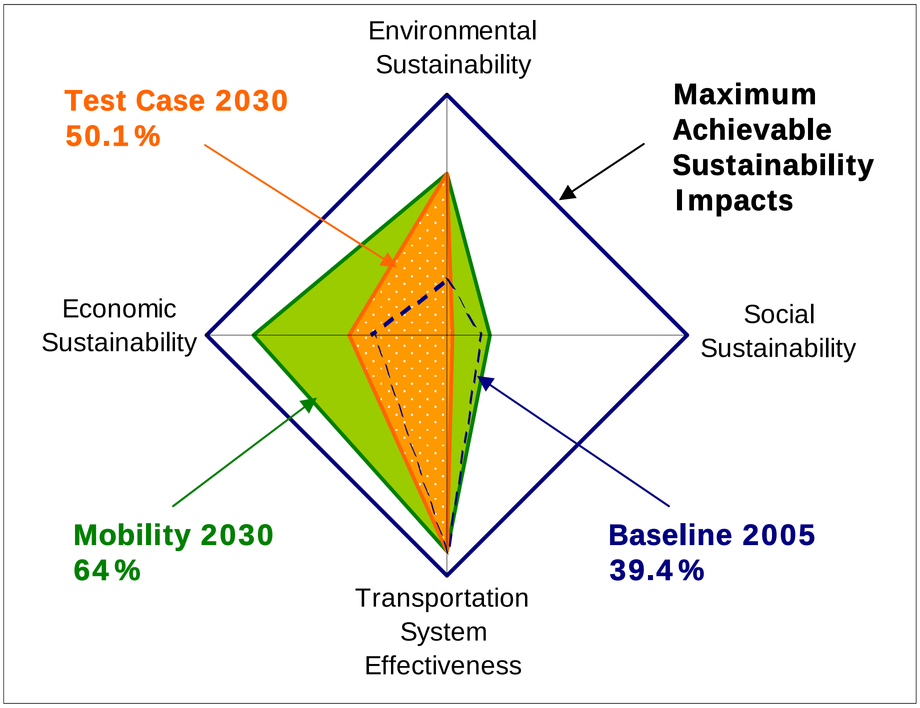

Figure 54 Sustainability with Least and Most Favorable Weighting Scenario.

Using these extreme weighting scenarios, the decision support tool effectively captures the possible impacts of decisions resulting from different regional priorities. Figures 55 through 57 show different boundaries of sustainability outcomes of three plan alternatives depending on three weighting scenarios: 1) most favorable scenario, 2) neutral scenario, and 3) least favorable scenario. Thus, the area between the largest solid rhombus and the smallest empty diamond is a feasible zone where all possible sustainability diamonds can be drawn based on different regional priorities. The dashed diamonds filled with dots are possible sustainability outcomes based on the neutral weighting scheme which assigns evenly distributed weights on each sustainability dimensions and performance measures.

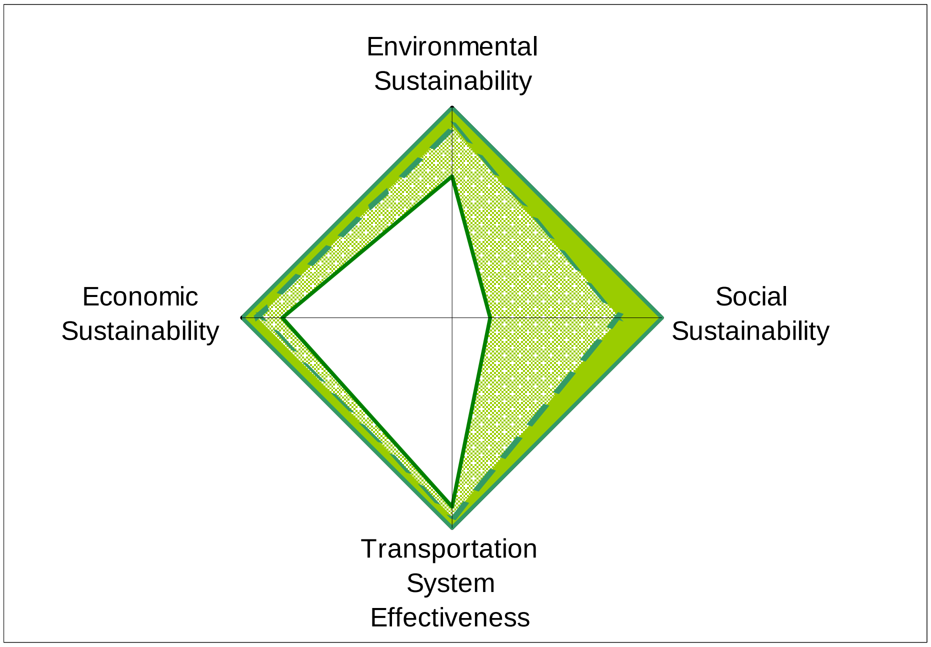

Figure 55 Sustainability of Mobility 2030 with Changing Regional Priorities.

These dynamics enable decision makers to face how much their subjectivity on regional priorities influences the sustainability outcomes resulting from each plan alternative. Some plan alternatives, such as the Mobility 2030 in the study, may be less sensitive to weight changes while other plans are more sensitive to weight changes. Understanding these sensitivities inherent in each plan alternative is important in that decision makers should not just rely on a resulting index but must also examine the relevance of (1) weights and (2) evaluating process relative to the vision, goals, and priorities for their respective regions (Jeon et al., 2007).

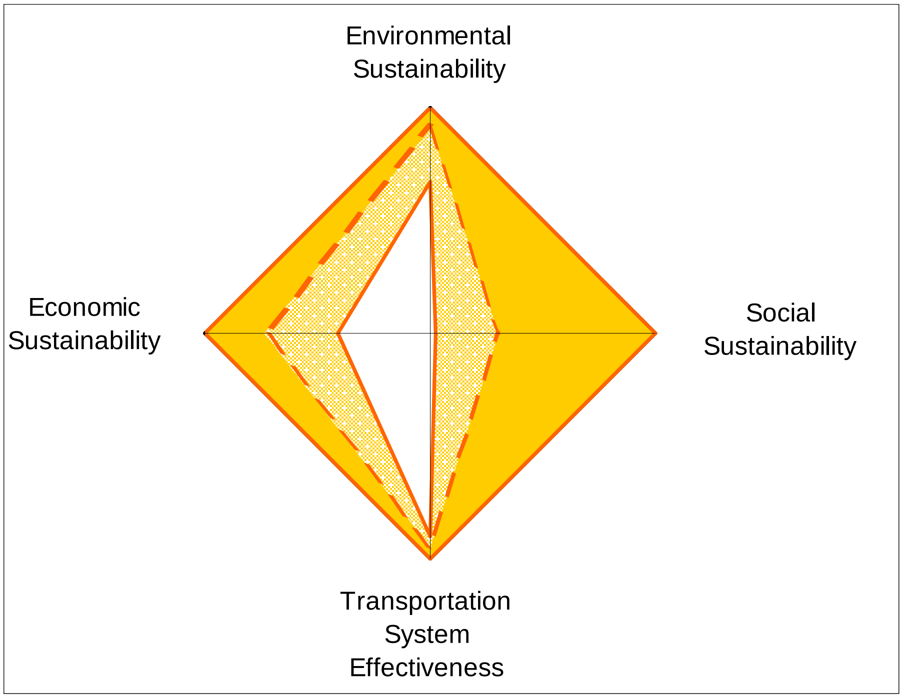

Figure 56 Sustainability of Test Case 2030 with Changing Regional Priorities.

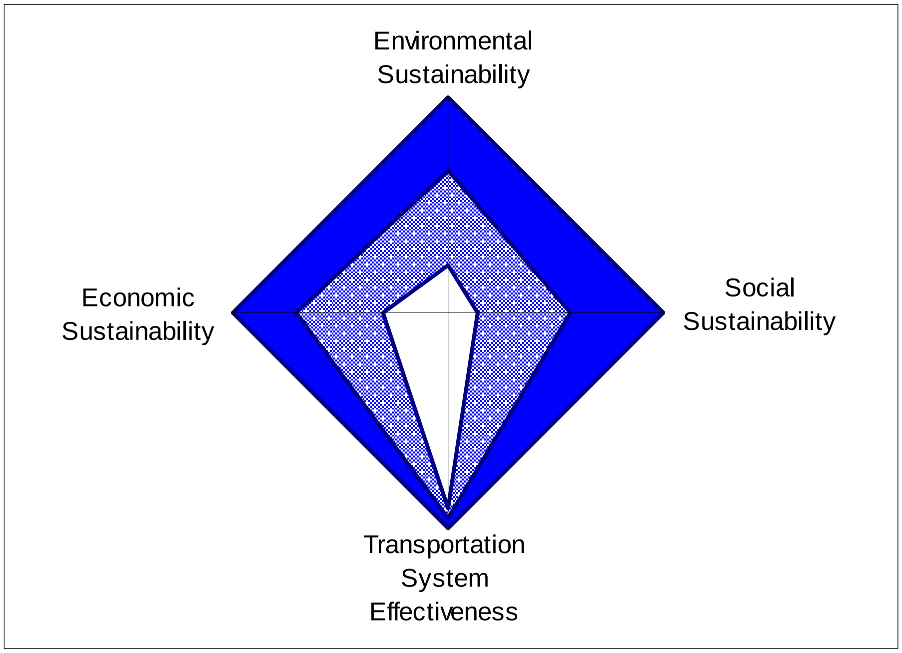

Figure 57 Sustainability of Baseline 2005 with Changing Regional Priorities.

CHAPTER 8

CONCLUSIONS

8.1. Summary and Conclusions

As interests in sustainability have grown over the past several years, an increasing number of Departments of Transportation (DOTs) has continued to include sustainability in their mission statements. While quite a number of sustainability initiatives have discussed various definitions and performance measures of sustainable transportation systems, very few regional agencies have developed planning tools that successfully incorporate a broad range of sustainability considerations in the development of long-range plans or transportation improvement programs (TIPs). Although there is no standard definition for transportation sustainability, performance measures, evaluation methodologies, planning for sustainable transportation systems should at the very least incorporate their broader impacts on system effectiveness and efficiency, environmental integrity, economic development, and the social quality of life. This study develops a working definition of sustainability from various proposed definitions, and demonstrates a feasible methodology for evaluating and quantifying sustainability performance measures, and thus incorporating sustainability considerations into the regional transportation decision-making process. It is important to note that the methodology is developed to capture the vision, goals, and objectives of any particular region, as they pertain to sustainability, and to allow for changes to be incorporated as the vision continues to evolve.

The literature review indicates that the present status of addressing sustainability in transportation planning is more focused on the effectiveness and efficiency of transportation systems as well as the resulting environmental impacts, and less on economic and social impacts. In addition, case studies on sustainability issues around the world imply that different metropolitan regions may have different sustainable development priorities. Thus, sustainability parameters should be determined based on regional priorities usually captured in regional planning goals and objectives for the sustainable development of the region. Furthermore, sustainability evaluation methods would have to be versatile enough to reflect evolving priorities for a particular region as a function of time as its needs change.

Through a case study of Atlanta Metropolitan Region, the study evaluates competing transportation and land use plans based on a broad range of sustainability parameters using relevant spatial and environmental analyses. Three different transportation and land use plan alternatives are used in the analysis: (1) the Baseline 2005, (2) the Mobility 2030, and (3) the Test Case 2030 plans. First of all, the sustainable development priorities for the region's transportation systems are identified based on pertinent sustainability issues and regional goals. Second, representative performance measures for the four sustainability dimensions are determined and evaluated for the selected long-range regional plans. Third, a dual sustainability index system is developed and used to demonstrate how decision makers can synthesize these evaluation results and identify superior plans for predetermined objectives. A multiple criteria decision making (MCDM) method enables the aggregation of individual performance measures into four basic indexes and further into a composite sustainability index based on regional goals and priorities. Finally, a decision support tool is proposed to visualize dominance and tradeoffs when evaluating alternatives and to effectively reflect changing regional priorities over time. Extensive sensitivity analysis conducted on the weights of the different sustainability dimensions as well as dimensional performance measures sheds light on which alternative best achieves different regional priorities and goals as a function of time and space.

The results indicate that the Mobility 2030 plan is a near-dominant alternative as it achieves the highest value of a composite sustainability index throughout all the possibilities of weighting schemes for sustainability dimensions and performance measures. The four sustainability dimensional indexes (i.e., system performance, economic, environmental, and social impacts), however, provide additional information on the relative strength of each alternative based on each sustainability dimension. The investigation of these dimensional indexes using the visualizing tool enables the decision maker to discover the dominance and tradeoffs between non-identical alternatives. While the Baseline 2005 and Test Case 2030 alternatives result in a comparable level of overall sustainability (under a neutral weighting scheme), the Baseline 2005 is a more equitable and healthier plan while Test Case 2030 is a more environment-friendly plan. Understanding these types of tradeoffs that are being made from plan to plan can be valuable for understanding the impacts of decision making on the region’s ability to achieve its current priorities, from a system-wide perspective.

The intent of sensitivity analysis is to provide practitioners with information on the alternative they are most likely to select if they weight the different dimensions and measures of sustainability in various ways, while indicating tipping points or switchover points of the composite sustainability index from one alternative to another. The sensitivity analysis suggests that regional priorities or weights play a critical role in deciding on the preferred plan alternative which may be only superior from the standpoint of what is considered important in that region. Using switchover information, the analyst can also provide adequate decision support information to decision makers by letting them know how the relative importance they have given to a particular criterion may result in a switch from one alternative to another. Furthermore, such sensitivity analysis exercises can function as a consensus building tool by providing decision makers with categories/families of weighting scenarios that result in the same decision on the preferred plan. The sensitivity analysis also enables decision makers to confront possible uncertainties inherent in a particular decision by pre-examining the expected outcomes of different weight assignments and by identifying the level of uncertainties. The visual decision support tool effectively captures a feasible range of possible impacts associated with each alternative depending on the weighting scenarios ranging from the least favorable to the most favorable scenarios.

The proposed framework should help decision makers with incorporating sustainability considerations into transportation planning and decision making as well as identifying superior plans for predetermined objectives. In particular, sustainability assessment can be incorporated at the planning level in order to influence decision making and to support policies that affect regional sustainability. The proposed decision support tool and the sustainability index system enable decision makers to consider the multidimensional nature of sustainability as well as important tradeoffs among the conflicting decision criteria. These tools are particularly versatile in capturing uncertainties commonly inherent in the decision making process by reflecting changing regional priorities and the impacts of subjective weights over time and space, and these dynamics are effectively conveyed using the visual tool.

8.2. Limitations and Future Research

Future research is directly related to some of the limitations of this study. First of all, the future plan alternatives used for sustainability evaluation were obtained in the beginning of the year 2006, and the data have been continuously updated until recently (September, 2007) throughout a 3-year process of Atlanta Regional Commission (ARC). The two 2030 analyses presented in this dissertation employed the same transportation network because at the time the analyses were conducted the new travel demand model outputs were not available. Hence, the two 2030 scenarios presented here still projected the same vehicle miles of travel and vehicle-related emissions, even though the different land use plans must necessarily lead to different values for both indicators. The Test Case 2030 plan evaluated in this study is also different than the most recently proposed final draft Envision6 Regional Transportation Plan. Further evaluation of the revised regional transportation plan would be needed to monitor the latest, most up-to-date progress in movement toward or away from regional sustainability.

Second, the performance measures actually evaluated to capture the sustainability goals and objectives of the Metropolitan Atlanta Region are somewhat limited with respect to comprehensiveness and effectiveness. Further development and quantification of sustainability measures will help incorporate the sustainability considerations more fully. For the environmental dimension, daily emissions of carbon monoxide (CO) and particulate matter (PM) should be also estimated along with daily emissions of VOC and

NO_x. For the economic dimension, some types of freight measures may have to be included to capture regional economic impacts of accommodating freight traffic. On the social dimension, the Human Impact Index (HII) used in this study is a highly simplified measure. Actual exposure to pollutant concentration is much more complicated issue due to the complex nature of predicting hourly pollutant concentrations and population movements for exposure assessment. Incorporation of improved population exposure metrics for PM emissions (downwind concentrations coupled with human activity predictions) would improve health impact assessments and more directly link the pollutant emissions to actual equity impacts for the transportation and land use plans. Integration of more refined exposure models should enable this measure to be fully incorporated in the social dimension of sustainability.

Third, performance measures in each sustainability dimension are not all independent. The analyses presented herein do not explicitly capture the correlation or interactions among system performance, the economy, the environment, and social quality of life. The composite sustainability index used in the study, for example, does not explicitly capture the correlation between transportation activity, emissions measures (in the environmental dimension), and human exposure measures (in the social dimension). Future research should proceed to incorporate broader environmental, economic, social impacts of transportation systems by modeling the interactions among these sustainability dimensions.

Fourth, the analysis was not able to capture the differences between the transportation activities that result from the implementation of the different 2030 land use scenarios because the new travel demand model outputs were not yet available from the planning agency when these analyses were conducted. Hence, the analyses are not based on a truly integrated transportation and land use model and so fail to capture equilibrium states generated by several iterations to simulate the interaction between the land use and transportation system, which affects trip-making, traffic volumes, on-road operating conditions, and regional emissions. The use of the final integrated transportation and land use model results for each scenario will enable analysts to better reflect the sustainability impacts of different transportation and land use plans.

Finally, the methodology presented identifies the best plan from the competing alternatives put forward, and not necessarily the best plan for regional sustainability. The comparison of transportation and land use plans developed for different metropolitan regions would enable the decision maker to track the sustainability competitiveness of their plans on some comparative scale of sustainability. Ideally, further research is necessary to allow for objective standard to be applied in determining which plans are sustainable from an absolute rather than a relative point of view. Also, more work is necessary to refine the MCDM method used to aggregate the individual performance measures into an index. There may be some value in exploring non-deterministic models (e.g., fuzzy or Bayesian decision making models) to effectively reflect uncertainties inherent in human decision making due to a lack of information or constraints in human thinking.

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