ASSESSMENT FRAMEWORK FOR THE SUSTAINABILITY OF TRANSPORTATION SYSTEMS

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A THESIS
IN
THE DEPARTMENT
OF
BUILDING, CIVIL AND ENVIRONMENTAL ENGINEERING

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF APPLIED SCIENCE (CIVIL ENGINEERING) AT
CONCORDIA UNIVERSITY
MONTREAL, QUEBEC, CANADA

AUGUST, 2014

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

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Entitled: Assessment Framework for the Sustainability of Transportation Systems

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Civil Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

ASSESSMENT FRAMEWORK FOR THE SUSTAINABILITY OF TRANSPORTATION SYSTEMS

Md Abdul Quddus

It is agreed that a sustainable transportation system has to satisfy today's needs with a positive influence on meeting future transportation demand. The major concerns in sustainability for most transportation agencies are related to (a) the safety issues for all potential users, (b) the system's efficiency in providing accessibility and mobility, (c) the potential of the transportation systems to enhance economic productivity and social equity, and last but not least (d) limiting and/or eliminating the negative impact on the natural environment. The assessment of a transportation system's sustainability should include the extent to which the decisions affecting transportation activity are optimized with respect to different environmental, social and economic criteria. Qualitative methods to assess transportation sustainability are found in many the studies. Even though there are few studies regarding quantitative assessment of transportation sustainability, they are for small-scale applications and with limited number of indicators. This thesis proposes a quantitative methodology to assess transportation sustainability that is flexible and comprehensive (i.e. independent of the type and scale of the transportation system analyzed). In this thesis, the criterions related to major concerns, generally referred to as indicators are grouped into sets that include specific goals and objectives, because an ideal sustainable transportation planning requires a balanced set of indicator targeting economic, social, and environmental sustainability. Using these indicator sets, a *Sustainability Index* is developed, which represents a weighted aggregated value based on the Analytic Hierarchy Processes principle. Therefore, the proposed methodology is organized as a comprehensive and flexible evaluation framework that provides a global assessment index. This methodology can be adapted to local assessment conditions used by transportation agencies to examine the conditions of the existing transportation infrastructure, as well as to predict the sustainability of future transportation developments.

# ACKNOWLEDGEMENT

Here I take the opportunity to offer my sincere gratitude to my supervisor, Dr. Ciprian Alecsandru, for his inspirational advice, encouragement and great support during my studies. It was a great pleasure working under his supervision.

Besides, I would like to dedicate my thesis to my wife Salina, daughter Faaizah and son Tausif. Without their great sacrifice and passions, this dissertation would not have come to end.

Last but not the least, I would like to thank my friends and colleagues – Omar, Homero, Javad, Hamed, Rashed and others for their immense support. I am grateful to them and miss them a lot.

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LIST OF ABBREVIATIONS

EUC:	European Union Council
GHG:	Greenhouse Gas Emissions
AHP:	Analytic Hierarchy Process
OECD:	The Organization for Economic Co-operation and Development
GDP:	Gross Domestic Product
LOS:	Level of Service
QM:	Quantitative and Monetarily Valued
QNM:	Quantitative and Non-monetarily Valued
Q:	Qualitative
QOL:	Quality of Life
PKT:	Person-kilometer Traveled
CBD:	Central Business Districts
LP:	Linear Programming
GP:	Goal Programming
TOPSIS:	Technique for Order Preference by Similarity to an Ideal Solution
CI:	Consistency Index
RI:	Random Consistency Index
CR:	Reason of Consistency
PSR:	Pressure-State-Response
TAC:	Transport Association of Canada
VMT:	Vehicle Mile Travelled

VKT:	Vehicle-km Travelled
SF:	Sustainability Footprint
VOC:	Volatile Organic Compound
ANOVA:	Analysis of Variance
SPSS:	Statistical Package for the Social Sciences
CANSIM:	Canadian Socio-economic Information Management System
SI:	Sustainability Index

CHAPTER 1
INTRODUCTION

Sustainability of a transportation system can be evaluated with respect to different criteria. From the supply services perspective, a sustainable transportation system should have the capability to fulfill the current and future transportation needs while minimizing, or avoiding the negative impacts in the long term. In general, a sustainable transportation system must be safe for its users and the surrounding environment, be efficient in providing accessibility and mobility, and enhance economic productivity and social equity, without negatively affecting the natural environment for the current and the future generations (Richardson, 1999, May et al. 2001, European Union Council, 2001, Litman et al. 2006.). Transportation sustainability can be achieved by ensuring that the contributing factors related to environmental, social and economic goals are optimally integrated into decisions affecting transportation activity. Therefore, it is necessary to know in detail the various goals corresponding to environmental, social and economic sustainability.

The environmental goal of sustainable transportation is to reduce the negative impacts on the natural environment (i.e. pollution prevention, climate protection and habitat preservation) and, thereby, generating the greatest possible improvement in the quality of life. To be specific, major environmental concerns are the amount of vehicle emissions, with special focus on greenhouse gas emissions; air, water, and soil pollution; resource generation and consumption capacity (especially fuel-resource depletion and overconsumption); recyclability of resources; and environmental stability in general.

The social component of a sustainable transportation system focuses on the contribution to the progress of the society in general. For example, any transportation development should ensure that the proposed or expected changes will not have detrimental effects for any socioeconomic stratum of the affected area. The major issues are to provide basic human needs, alleviate social disparities, ensure equity, enhance user's safety, improve accessibility, and tackle human health issues.

Finally, from an economic sustainability point of view, the transportation system should balance regional development and promote economic growth and long-term prosperity with cost-effective and competitive solutions (European Union Council, 2001, World Bank, 1996). The main focus area of economic sustainability are employment, efficiency, affordability, road traffic congestion, availability of mode choice, vehicle fleet size, etc.

This study aims to develop a methodology to quantitatively determine the impacts of different indicators on the transportation system's sustainability. These sustainability indicators are grouped into sets that accomplish specific objectives through sub-objectives and attributes. This methodology is organized as a comprehensive and flexible evaluation framework that is also adaptable to local assessment conditions as they become available to transportation practitioners and decision makers involved in the sustainability evaluation process. The analysis of the proposed methodology is based on the Analytic Hierarchy Process (AHP). The AHP was originally proposed by Saaty (1977) and is typically used as a tool for prioritization in support of multi-criteria decision analysis. The AHP is based on three basic steps: (*i*) organization of the problem in a hierarchical structure that reflects the relationship between different levels; (*ii*) paired comparison between positioned elements in a hierarchical level with respect to elements in the adjacent top level; and (*iii*) calculation of eigenvectors and eigenvalues, and check the consistency of the assessments.

This thesis consists of four chapters. Each chapter deals with a distinct but fundamentally integrated task. Chapter 2 briefly presents various characteristics of a sustainable transportation system, different approaches to modeling and achieving transportation sustainability, and several ways of evaluating the transportation system sustainability. Additionally, literature review includes various findings regarding sustainability indicators (e.g. criteria used to select indicators, classification of indicators, different methods to develop an indicators, etc.). Chapter 2 concludes with a review of the state-of-the-art transportation sustainability assessment framework. Chapter 3 proposes a methodology to assess the sustainability of a transportation system in the form of a comprehensive and flexible assessment framework. This chapter also describes the Analytic Hierarchy Process used to analyze the framework. Finally, chapter 4 summarizes the findings of the thesis and identifies possible development for future work.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

2.1 Assessment Indicators

2.1.1 Transportation System Sustainability Indicators

OECD (1993) defined the indicators as a parameter (or a value derived from a parameter) that gives information with regard to a particular phenomenon. In contrast, Gudmundsson (2000) described the indicators not as a parameter but rather as a selected and targeted variable used by the decision makers to reflect public concerns. Litman (2007) illustrated the indicators as variables used to evaluate progress toward goals and objectives. According to Steg and Gifford (2005), the indicators can be used to evaluate sustainability not only for the current transportation system but also for future developments. For example, indicators like commuting speed, congestion caused delay, variety and quality of the available transport options etc. can be used to assess the current transport system and other indicators specially related to macro-economic changes e.g., changes in GDP and employment levels could be used to assess the future transport system. Litman and Burwell (2006) suggest that indicators can be used to assess particular policies and to set system performance targets. For clarity, let us assume that a specific policy - congestion-reduction strategy is taken to support an increase in mobility for achieving economic sustainability. Roadway expansion; road and parking pricing; commute trip reduction programs etc. are the corresponding transportation related activities and motor vehicle travel is chosen as the indicator to measure the performance of the policy. Research indicates that beyond an optimal level of motor vehicle travel, the marginal productivity of increased travel declines, causing overall negative economic impacts. Research also shows that excessive vehicle use imposes external costs that can offset direct economic gains (Boarnet, 1997; Helling, 1997).

2.1.2 Criteria for Selecting Sustainability Indicators

According to Litman (2007) a set of sustainability indicators should reflect specific goals to capture the effects on economic, social, and environmental objectives. Therefore, an optimal sustainable transportation planning can be achieved via a balanced set of indicators reflecting economic, social, and environmental objectives. Litman and Burwell (2006) suggest that for selecting indicators, one should consider balancing among usefulness, convenience, ease of collection, cost, and comprehensiveness. Because a smaller set of indicators for which data is easily available may be more attractive to use but, may overlook important impacts, in contrary, more comprehensive data set may require a more complex data collection process and/or higher associate costs. Kolak et al. (2011) puts an emphasis on properly defining the indicators before selection. Litman (2007) suggests that it is equally important to understand the perspectives, assumptions, and limitations of each indicator, because different types of indicators reflect different perspectives and assumptions which significantly influence analysis of results. For example, the use of just the road level of service (LOS) to compare among different roadway systems without additional information might be misleading because, while LOS primarily reflects automobile congestion, it cannot explain the quality of other transportation modes, the land use accessibility, transport diversity, and the distribution of destinations.

2.1.3 Classification of indicators

According to the type of data used Black et al. (2002) classified sustainable indicators at three levels: at *level 1*, the impacts of these indicators are both quantified and monetarily valued (QM) (e.g. cost benefit analysis to measure economic efficiency), at *level 2*, the impacts of these indicators are quantified but non-monetarily valued (QNM) (e.g. average speed of transport to measure reliability) and at *level 3,* these indicators are qualitative assessments (Q) (e.g. satisfaction rating of transport system to measure local environmental quality). Furthermore, Kolak et al., (2011) categorized sustainability indicators as Economic indicators, Social indicators and Environmental indicators. Details of these indicators can be found in Steg and Gifford (2005) where the authors state that Economic indicators measure possible effects on economic welfare through macroeconomic changes, economic efficiency, income distribution and unemployment rate. Social indicators reflect effects on social and individual quality of life, such as health and safety. Environmental indicators measure the effects on environment, such as natural resources use, pollutant emissions, waste generation, effects on quality of soil, water and air etc.

Fedra (2004) classified sustainable indicators into 5 groups - Driving force indicators, Pressure indicators, State indicators, Stress indicators, Impact indicators and Response indicators (DPSIR). Driving force indicators are responsible for the actual demand of transportation. Driving force indicators can be further subdivided into three categories - demographic indicators (e.g. size and age distribution of population, presence of high-tech activities etc.), land-use indicators (e.g. the spatial distribution of population and city functions, such as residential, commercial, recreational, employment zones) and economic indicators (e.g. employment in services, the tele-working and commuting patterns etc.). Pressure indicators measure the pressure on people and the environment due to driving force (e.g. emissions, natural resources and energy consumption, total auto and public passenger transport demand, and average distance travelled total in-vehicle-travel times etc.). State indicators measure the state of the environment caused by pressures (e.g. excess of air quality standards reported as frequency of violations per year, % of population exposed to noise levels above 65 dB, increased fragmentation of habitats, etc.). Impact indicators measure the effect due to the changes in state (e.g. ill health, time losses, or increased costs etc). Response indicators measure initiatives/action taken as a result of the impact (e.g. regulation, taxes, investment etc.). Figure 1 summarizes a possible classification of indicators.

2.1.4 Methods to Develop Indicator

Ramani et al (2011) suggested that the performance indicators could be developed through *a workshop process*, where in the presence of key personnel, stakeholders and potential users of the final research product, various strategic goals and related objectives are set and defined.

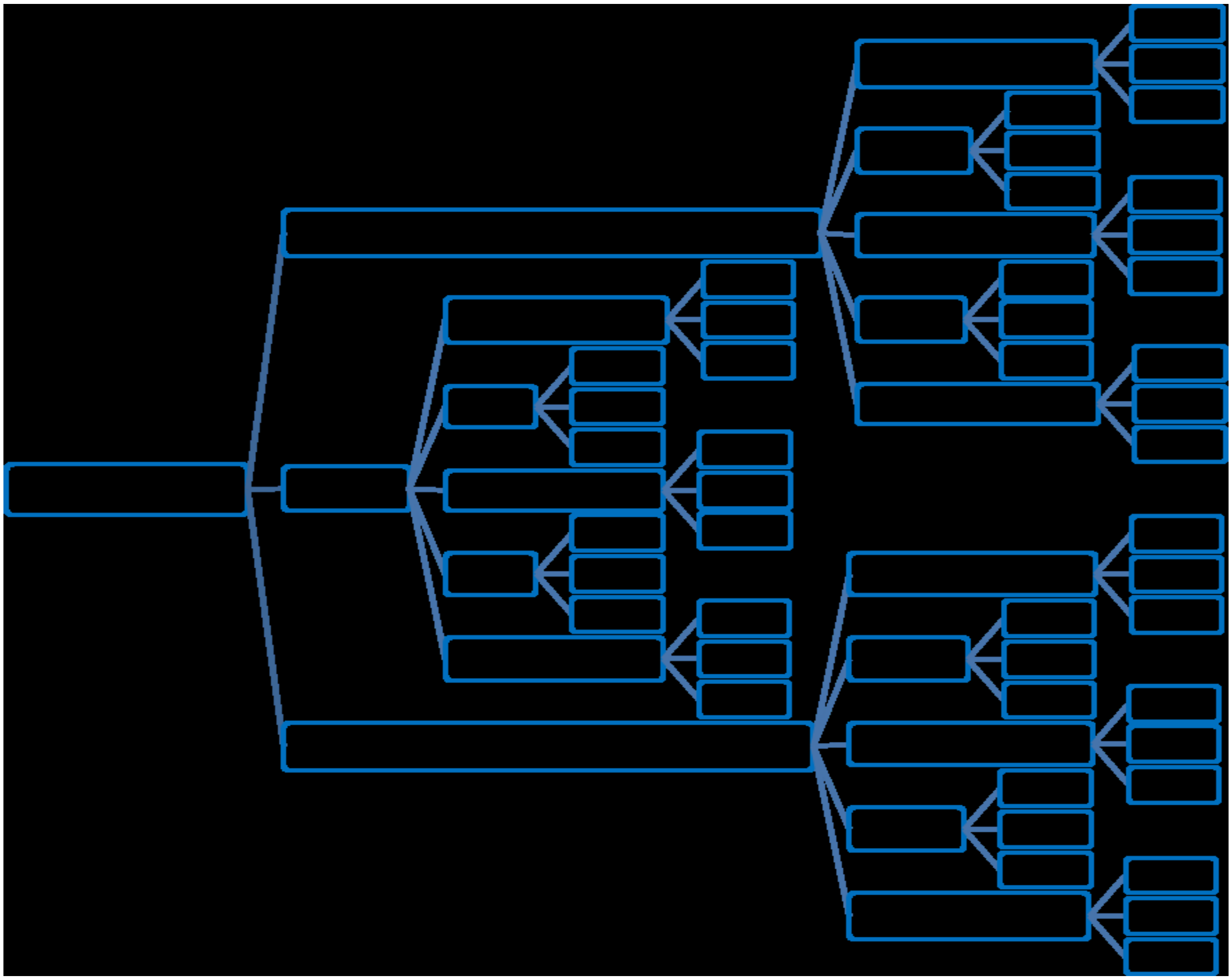

Figure 1: Classification of Indicator

Then each objective is linked to a measurable indicator that could be used in the sustainability evaluation. Application of the Delphi method makes this process more reliable. In the Delphi method participants rank individually the different components of the system (i.e. goals, objectives, indicators etc.) in order of importance and rate those on a scale from 0 to 1, with explanation of each individual ranking. Afterwards the scores are adjusted and averages are calculated for the various elements. Hart (1997) recommends many points that should be considered during ranking and rating. They are:

- How well does the indicator point the direction of sustainability? For example both water pollution and emissions indicators point out the direction of sustainability but during ranking and rating, one should consider which one of the two is more significant.

- Does the indicator focus on local sustainability at the expense of global sustainability? In other way, one indicator should not try to be better off by making another indicator worse off in achieving sustainability.
- Is the indicator understandable only by experts or by the community at large?
- Is the indicator developed, accepted, and used by the community?
- Does the indicator provide a long-term view of the community?
- Is the indicator based on information that is accurate, reliable, and accessible?

Nathan and Reddy (2011) propose a framework for indicator development by considering the urban transportation sector as a black-box and analyzing the system using a set of input (e.g. no of vehicle) and output (desirable e.g. mobility and undesirable e.g. pollution) variables. The goal is to get maximum desirable outputs with minimum inputs and minimum undesirable outputs from the sustainability point of view.

Jeon et al. (2005) develop *a unified three dimensional framework* to choose the proper indicator for sustainable development.

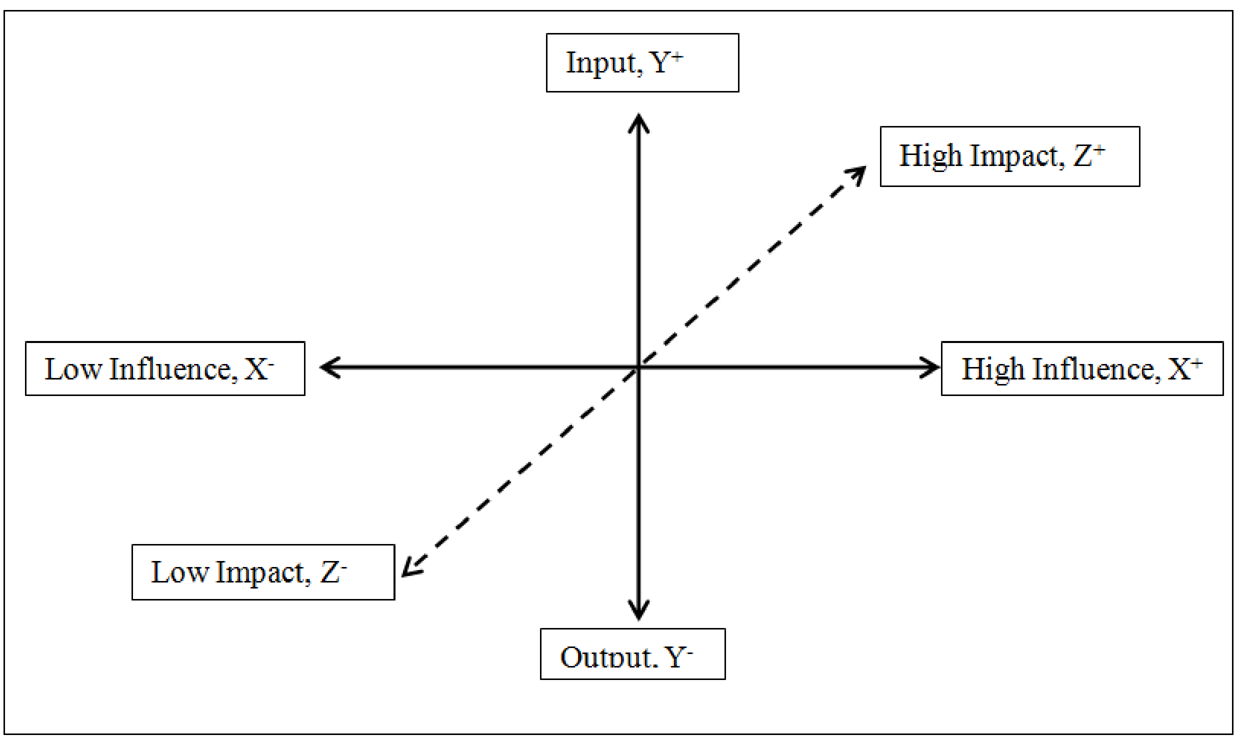

Figure 2: Unified framework for developing indicator systems (modified, Jeon et al. 2005 P-42)

In Figure 2, the x-axis denotes the level of influence an agency has over this indicator. Here, x^+ means high influence and x^- means low influence; the y-axis denotes whether the indicator is an input or an output of the system - y^+ means input and y^- means output of the system; and the z axis denotes the relative level of impact the indicator has on achieving sustainability - z^+ means high impact and z^- means low impact on achieving sustainability. For developing policies, planning procedures and analysis tools to enhance sustainability, agencies try to take the indicators which fall in the (x^+, y^+, z^+) zone. Because this zone is related to the causal factors (inputs, *y*+ axis) they have the most significant effect on high impact areas (*z*+ axis) relative to creating a sustainable transportation system within the domain of highest influence or control (*x*+ axis).

Black et al. (2002) proposed that for appropriate indicators selection, one has to identify specific objectives and introduced hierarchical diagrams to generate indicators. This diagram links the goal (at the top) with higher level objectives. These higher level objectives were linked with different objectives and finally with the precisely defined lower level objectives at the bottom layer. Each precisely defined objective is than attached with the appropriate performance indicators or the lower order action along with measurable attributes. The author introduced three hierarchical diagrams to generate indicators - one for unsustainable transportation, another for sustainable transportation and the other for urban form and sustainable transportation. For pertinence to our study, only the hierarchical diagram for sustainable transportation (Figure 3) is included. To generate environmental sustainability indicators, the author focuses on the fossil fuel depletion due to fuel consumption, global warming due to GHG emissions, local pollution due to vehicle emission and a few other environmental issues.

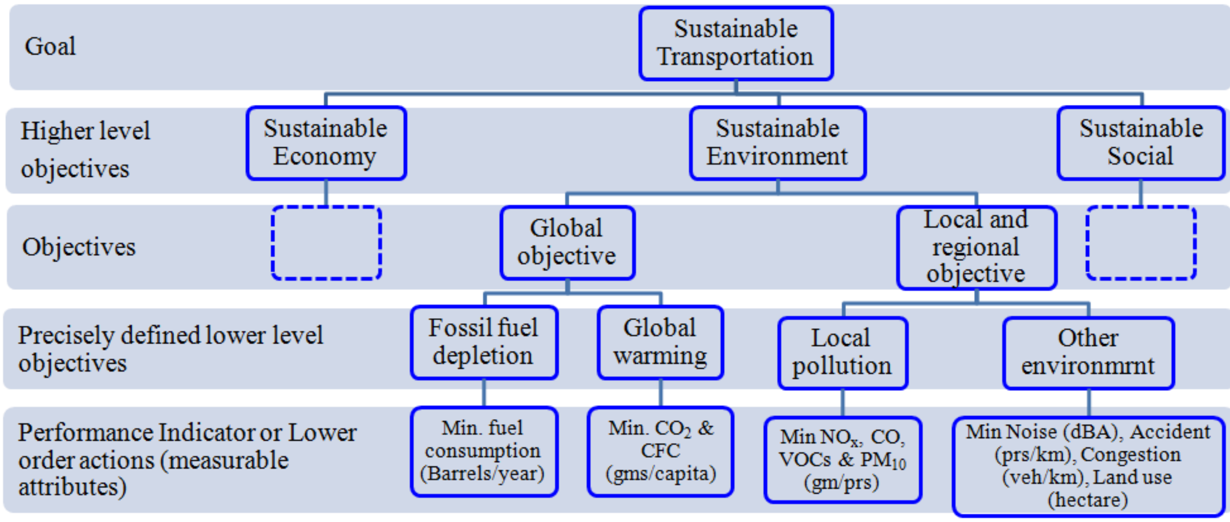

Figure 3: Hierarchical diagram for sustainable transportation (modified, Black et al, 2002, p-191)

2.1.5 Indicator's Evaluation Methods

Litman (2007) put emphasis on identifying trends, predict problems, and establish baselines for assessing an indicator. Black et al. (2002) proposed several empirical approaches to assess an indicator.

The first method is called *Exploratory and Graphical Method.* This method includes data analysis, descriptive statistics and correlation analysis which can be useful to understand the trends of different indicators. For example, in order to analyze the indicator "person-kilometers (prs-km)" of journey-to-work travel, the author makes a cross-sectional analysis of journey-to-work travel (prs-km) by all transportation modes vs. distance from the central business districts (CBD) in Sydney, based on 1961 and 1996 census data (Figure 4). The graph shows that with greater population in 1999, the prs-km was greater than that of 1996 which is expected. But the data plotted in the graph also shows that there is a major increase in prs-km for distances more than 20 km away from CBD. This is an indication of the urban sprawl effects.

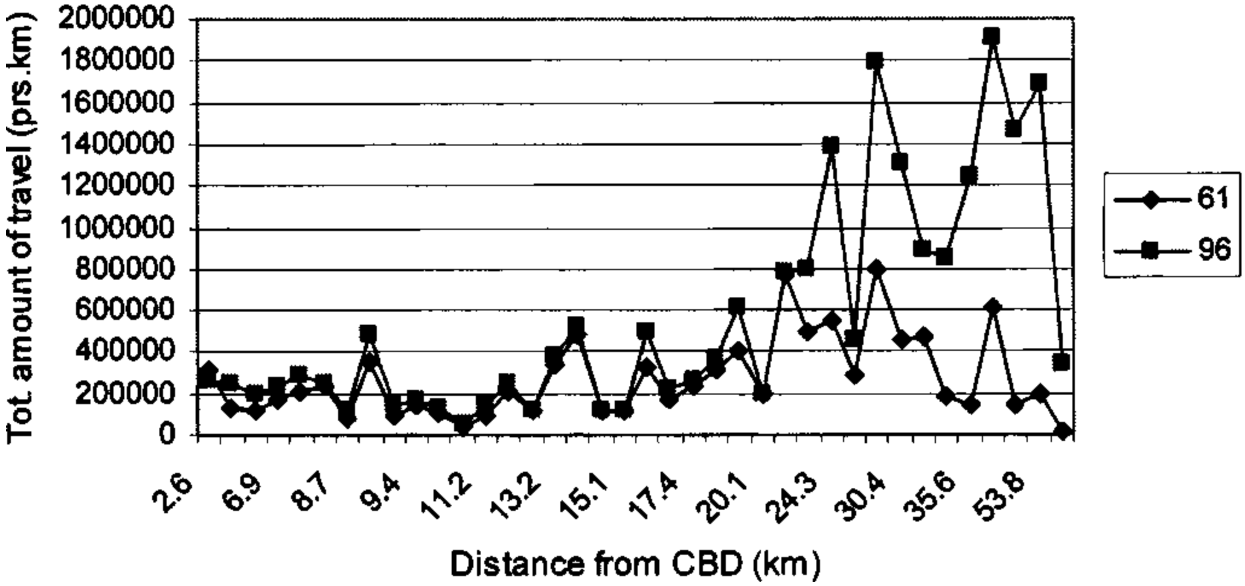

Figure 4: Total travel from CBD in Sydney, based on 1961 and 1996 census data (Black et al, 2002, Fig.4, P-192)

This method also can be used to check frequency distribution and correlation analysis of the indicators. The study shows that automobile journey-to-work prs-km is linearly correlated with population density (Figure 5) and nonlinearly correlated with accessibility to employment (Figure 6).

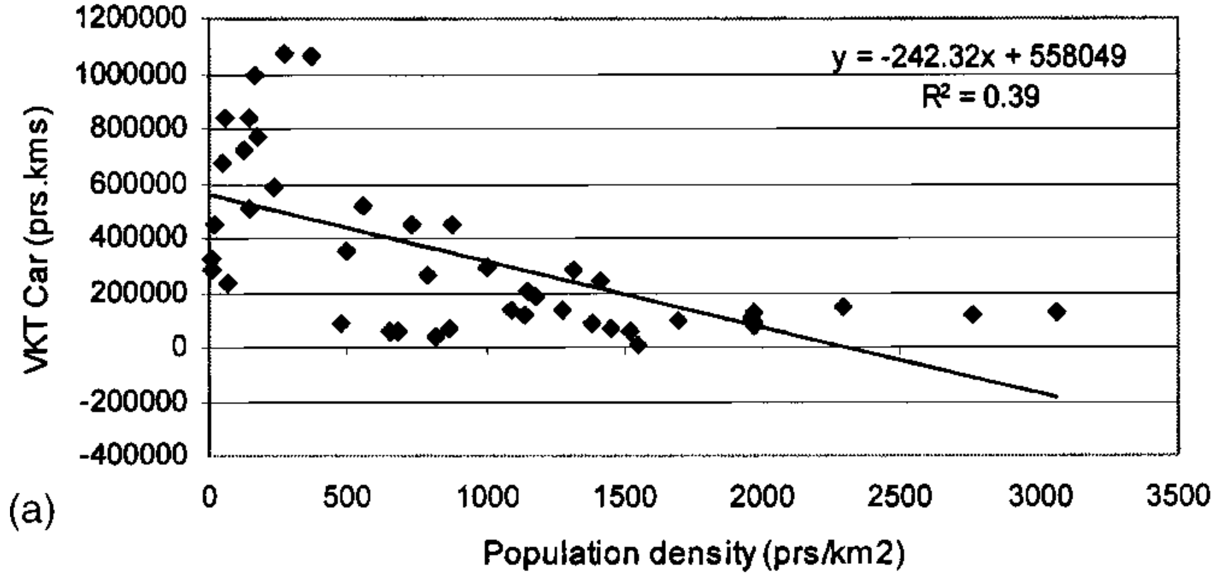

Figure 5: Relationship between gross population density and VKT by automobile in Sydney, based on 1996 census journey-to-work data (Black et al, 2002, Fig.5a, P-193)

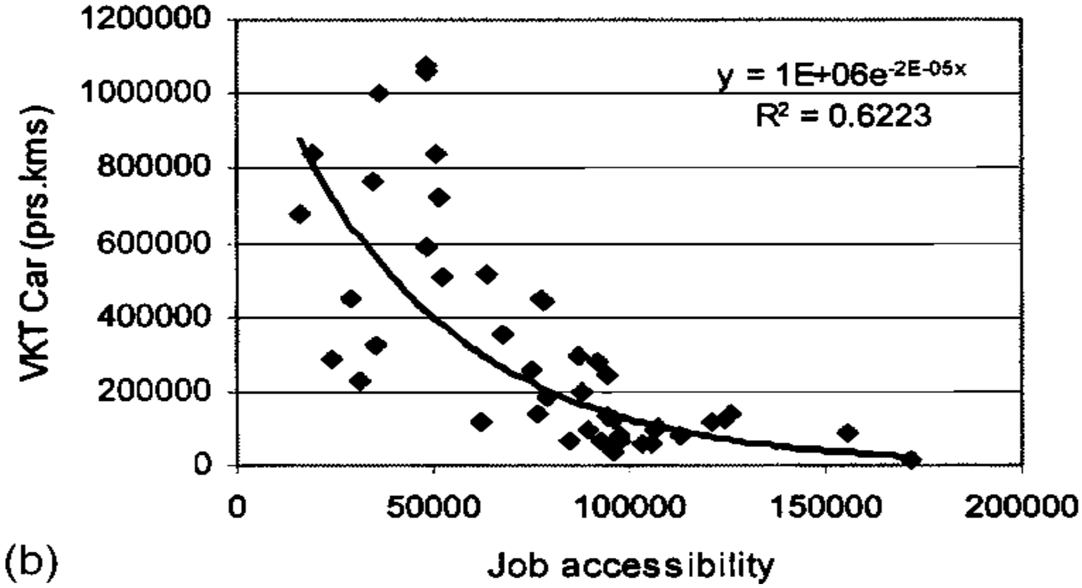

Figure 6: Relationship between job accessibility and VKT by automobile in Sydney based on 1996 census journey-to-work data (Black et al, 2002, Fig.5b, P-193).

The second analysis method is *Statistical Maps*, which can be used to show the trends of indicators in different zones. For example, Figure 7 shows that higher amount of journey-to-work travel by all transportation modes occurs at peripheral suburbs of Sydney. The third method is *Regression Analysis*, which could be used in transportation engineering and planning to forecast indicator values by applying well-known technique of least-squares, which minimizes sum of squared errors.

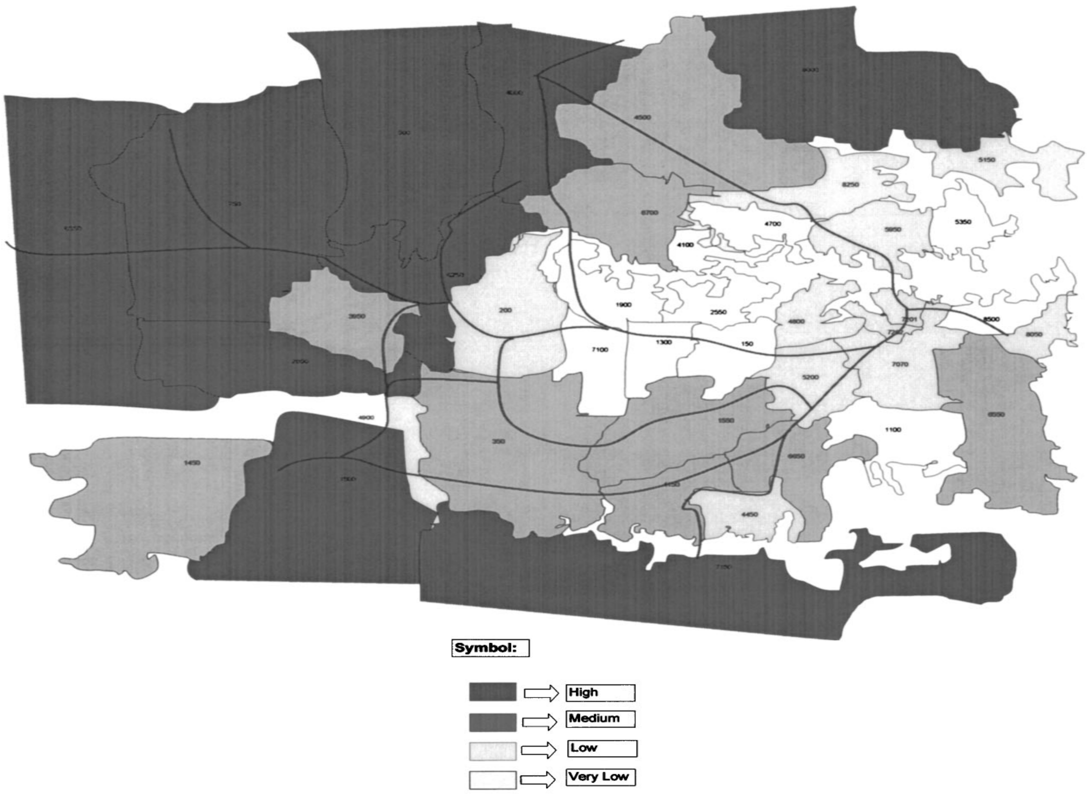

Figure 7: Map of total amount of journey-to-work travel by all transportation modes, Sydney, 1996. (Black et al. 2002, Fig.6, P-194).

2.2 Sustainable Transportation

2.2.1 Characteristics of a Sustainable Transportation System

From the literature search, it is observed that various researchers describe sustainability of transportation system in different ways. In 1992 the OECD's Brundtland Commission identified the sustainable development concept as "the society's ability to meet the needs of the present without compromising the ability of future generations to meet their own needs." In 2005 Richardson acknowledged that "needs" in the above definition may as well refer to "transportation needs". Litman (2003) explains that without coordinated decisions among different sectors, groups, and jurisdictions it is not possible to achieve sustainability. Kennedy et al. (2005) suggests that moving towards a sustainable urban transportation involves provision of accessibility and generation of wealth by cost-effective and equitable means, while safeguarding health and minimizing the consumption of natural capital and the emissions of pollutants. According to Litman (2009), sustainability reflects a concern for indirect and long-term impacts (such as natural resource depletion and ecological degradation including climate change) by ensuring that local, short-term decisions are consistent with the expected long-term impacts (for example, congestion reduction by increasing road capacity or construction of a new road is not sustainable, because it leads to increased vehicle demand and will cause environmental degradation, but congestion reduction by improving land use accessibility, congestion pricing, mode shifting is a more sustainable approach). In addition, various authors and organizations define environmental sustainability, social sustainability, and economic sustainability separately, as independent assessment criteria. Next, the details of each of the three sustainability assessment criteria are provided.

With respect to the environmental criteria, Boschmann and Kwan (2008) consider that environment sustainability is mostly concerned with resource depletion and overconsumption (e.g. negative impacts related to air, water, and soil pollution, energy crises, etc.). According to Nathan and Reddy (2011) environment sustainability in transportation is related to the renewability of resources and to the maintenance of cleaner environment for the current and the future generations.

From the socio-sustainability perspective, a World Bank report (1996) describes social sustainability as addressing the transportation needs of the less affluent and supports equitable sharing of benefits of transportation by all sections of society. Sanchez et al. (2003) recognized that the prioritization of highway development over public transportation has had inequitable effects on low-income populations, often restricting their ability to access social and economic opportunities, including employment opportunities and education.

Finally, with respect to economic sustainability, Nathan and Reddy (2011) propose that economic sustainability is an issue of the productivity of resource use, contribution to the economy and satisfaction of economic needs of individuals. Boschmann and Kwan (2008) described the economic sustainability of transportation related to the ability to promote economic growth, expansion, and long-term prosperity. According to a World Bank report (1996) economic sustainability of transportation ensures continuing capability to serve transportation demand with cost-effective and competitive solutions. The report also suggests that economic sustainability can be achieved by optimizing vehicle fleet size, and maximizing transportation infrastructure capacity.

2.2.2 Guidelines for Sustainable Transportation

The first step in modeling sustainable transportation is the identification of objectives. Several recent studies proposed that transportation sustainability can be measured by estimating the level of accomplishment of specific objectives. For example, Black et al. (2002) identify a list of six major objectives related to transportation sustainability: economic efficiency, contribution to economic growth, protection of the environment, equity and social inclusion, users' safety, and the level of livability of communities. Among the above objectives, economic efficiency and contribution to economic growth are related to economic sustainability. Meanwhile, equity, social inclusion, users' safety, and the level of livability of communities are related to social sustainability. In addition, protection of the environment is related to environmental sustainability. Litman and Burwell (2006) described that transportation sustainability can be achieved via three objectives: economic sustainability, environmental sustainability, and social sustainability. Steg and Gifford (2005) further claim that a sustainable transportation system has to find the appropriate balance among different targeted objectives. Guenther et al. (2009), state that a truly sustainable system is not only balanced among objectives, but is also maximized to the benefits of each objective.

After the objectives are established, the next step is to identify a set of attributes associated with each objective. Richardson (1999) pointed out that a sustainable transportation system is one in which fuel consumption; vehicle emissions, safety, congestion, and accessibility are of such levels that the system can be sustained for the indefinite future. In a report in 2001, the European Union Council described a detailed set of guidelines. According to this report, a sustainable transport system should be accessible, equitable and affordable, operate efficiently, have a positive impact on balancing the regional development, offer different choices of transport modes, and support a competitive economy. The report also mentioned that the sustainable transport system should limit the emissions and waste within the planet's ability to absorb them, minimize the impact on land and the generation of noise, use renewable resources at or below their rates of generation, and use non-renewable resources at or below their natural rates of development of renewable substitutes. In addition, Ramani et al (2011) emphasize on the environmental aspect by eliminating the toxic pollution.

2.2.3 Selection of objective, sub-objects and attributes

Litman and Burwell (2006) used the following – for economic sustainability the objectives are accessibility, affordability, freight efficiency, planning and the corresponding indicators are average commute travel time, portion of household expenditures devoted to transport, speed of freight, degree to which transportation reflected least-cost and investment practices respectively. For social sustainability, the objectives are safety, health and fitness, community livability, equity and related indicators are crash disabilities and fatalities, percentage of population that regularly walks and cycles, and degree to which prices reflect full costs respectively. For environmental sustainability the objectives are climate change emissions, other air pollution, water pollution, land use impacts, habitat protection, resource efficiency and related indicators are per capita fossil fuel consumption and CO_2 and other climate change emissions, per capita emissions of conventional air pollutants, per capita vehicle fluid losses, per capita land devoted to transportation facilities, preservation of wildlife habitat respectively.

Ramani et al (2011) describe five attributes for economic sustainability; reduced congestion measured by travel-time index, improved reliability measured by buffer index, optimized land-use mix for development potential measured by land-use balance, improved freight movement measured by truck throughput efficiency, preserved value of transportation assets measured by average pavement condition score and capacity addition within available right-of-way. The authors mentioned that social sustainability can be achieved by enhancing safety and the corresponding attributes are reducing crash rates and crash risk measured by annual severe crashes per mile and improves traffic incident detection and response measured by percentage lane-miles under traffic monitoring. The authors also point out that environmental sustainability can be obtained by complying with ambient air quality standards measured by air quality index and by reducing GHG emission measured by daily CO_2 emissions.

Litman (2007) puts emphasis on mobility, affordability, and congestion reduction for economic sustainability; cohesion, livability, health, accessibility and equity for social sustainability; and climate change, pollution prevention, habitat loss, and non-renewable resource depletion for environmental sustainability. The author also provides a list of indicators in each category – economic, social and environmental – separately.

Boschmann and Kwan (2008) mentioned that environmental sustainability should be concerned with the attribute of resource depletion and overconsumption as well as air, water, and soil pollution. Economic sustainability should be concerned with economic growth, expansion, and long-term prosperity. Social sustainability should be concerned with equity, social exclusion, and quality of life.

Zegras (2006) mentions that in the SPARTACUS project, the attributes for environmental sustainability are air pollution and consumption of natural resources. The indicators related to those attributes are also cited here. For social sustainability the project mentions the health, equity, safety and opportunities. The indicators related to these are also given.

2.2.4 Indicator selection

Chang et al (2009) used NO_x, CO., VOCs, and CO_2 per passenger - km as indicators to compare the environmental sustainability between bus rapid transit and light rail trains. Steg and Gifford (2005) claim that economic indicators have to be macroeconomic changes, GDP, economic efficiency, income distribution and unemployment rates. Environmental indicators should be resource use, emissions and waste, and quality of soil, water and air. Social indicators should be related to individual quality of life and provide a table of 22 quality-of-life indicators. Jeon and

Amekudzi (2005) listed a total of 177 indicators and metrics used by the 16 initiatives into 5 groups: economic, transportation related, environmental, safety oriented and social-cultural / equity-related. Kolak et al (2011) used environmental indicators as energy consumption, GHG emission, acidification and particulate formation; economic indicators as car share, share of non-motorized transport, share of freight transport, contribution to GDP, and contribution to employment; and social indicators as number of injuries, number of fatalities, quality of public transport, time to next public transport stop, time to get to work place and car ownership to evaluate the sustainability of transport networks. Nathan and Reddy (2011) provide 19 economic indicators, 18 social indicators and 17 environmental indicators. Centre for Sustainable Transportation develop a list of 14 sustainable transportation performance indicator among them 7 are environment indicators 6 are economic indicator and 1 social indicator.

2.2.5 Evaluation of Transportation Systems Sustainability

Most of the time evaluation of transportation sustainability is not possible by a single indicator, rather we need to combine a set of indicators into a single value sometimes referred to as a sustainability index (Lomax et al. 1997). Black et al. (2002) proposed to use linear programming optimization to determine the trip distribution that yields the minimum cost for the system. The optimization problem is subject to origin and destination constraints similar to the fully constrained gravity models with an additional constraint of omitting negative trip flows in the optimal solutions. Guenther et al (2009) used Goal Programming to achieve sustainability. In their study, each indicator set (i.e. economic, environmental, and social) is given a goal (G), and deviations (Z) from these goals are minimized. Kolac et al. (2011) utilized the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method, which is a multi-attribute evaluation process based on the principle that the selected alternative is the closest from the ideal solution and has the least negative impact. Using the TOPSIS method the study found the relative ranking of transportation system of 15 countries. This study uses AHP as an analyze tool.

2.2.4.1 Analytic Hierarchy Process (AHP)

The AHP was developed by Saaty (1977) and according to Dutra & Fogliatto (2007), AHP is one of the tools in support of multi-criteria decision-making with the highest number of applications reported in literature, particularly in issues involving subjective assessments. Vaidya & Kumar (2006) conducted a survey of AHP applications in the multi-criteria decision analysis. They analyzed a total of 150 application papers related to engineering, education, industry and government sectors where 27 of them were critically analyzed. They concluded that AHP is one of the most popular options used in the theme area of selection and evaluation and is going to be used widely in the future. Moreover, Guglielmetti et al. (2005) performed a comparison of AHP and other methods of multi-criteria analysis. The methods were assessed for their performance, characteristics in the data input, data output and interface between decision maker and method. The authors identified the following features of AHP that provide an advantage in comparison to the other methods: (i) it is a structured decision-making process that can be documented and repeated; (ii) it applies to situations that involve subjective judgments; (iii) it uses both quantitative and qualitative data; (iv) it provides measures of consistency of preferences; (v) it provides a wide documentation on practical applications in literature and (vi) it is suitable for groups.

2.2.4.2 Working Principles of Analytic Hierarchy Process (AHP)

The AHP is based on ***three basic steps***.

Step one is the organization of the problem in a hierarchical structure that reflects the relationship between different levels.

Step two is the construction of matrices of comparisons which is the reciprocal and square with unit values on the main diagonals. Its general format is given in Table 1.

Table 1: General format of the comparison matrix

	Element 1	Element m	...	Element D
Element 1	1	a_{1m}	...	a_{1d}
Element m	$1/a_{m1}$	1	...	a_{md}
...	...	...	...	...
Element D	$1/a_{1d}$	$1/a_{md}$	...	1

This matrices depicts paired comparisons between positioned elements in a hierarchical level relative to elements in the adjacent top level. The m^{th} row of the matrix of comparisons displays the result of comparisons between the element m and the other m-1 elements of the matrix. For a hierarchical level showing D elements, a total of $D * (D - 1)/2$ comparisons are required for filling the matrix of comparisons. The greater the number of hierarchical levels and the number of elements in each level, the more complex will be the analysis with a higher chance of error. The comparison matrix is designated by A_{le} if the element e on level l is used as a criterion for comparing elements in a lower level directly connected to l. Next, a priority vector is calculated for each comparison matrices A_{le}. The priority vector of A_{le} is designated by w_{le} = (w_1, w_2, ..., w_D). When comparing two elements m and n, we are, in fact, estimating the ratio of their weights of importance, that is $a_{mn} = {}^{w_m}/_{w_n}$. Elements in A_{le} are designated by $a_{mn} \quad m, n = 1, \ldots, D$, where $D \times D$ indicates the size of A_{le}.

Saaty (1990) proposed the following fundamental ranking scale for the value of a_{mn}.

Rank 1: Equal Importance - Two elements contribute equally to the objective.

Rank 3: Moderate Importance - Experience and judgment moderately favor one element over another.

Rank 5: Strong Importance - Experience and judgment strongly favor one element over another.

Rank 7: Very Strong Importance - An element is strongly favored and its dominance demonstrated in practice.

Rank 9: Extreme Importance - The evidence favoring one element over another is of the highest possible order of affirmation.

Ranks 2, 4, 6, 8 are intermediate values between the two adjacent distinct rankings that could be used when a compromise is needed.

Step three calculates the eigenvectors and eigenvalues, and checks the consistency of the arrays of comparisons from eigenvalue λ. For perfect consistency, $\lambda = D$ for any matrix of order D. For $\lambda_{max} > D$, Saaty (1977) proposes a consistency index (CI) given by: $CI = \frac{(\lambda_{max} - D)}{(D-1)}$

When the order of comparison matrix (D) increases, it is very difficult to find the consistency. For this reason, the index *CI* should be compared to a random consistency index *RI*. Alonso and Lamata (2006) calculated RI for 500000 matrices. The values of *RI* for arrays of different orders calculated by them are shown in table 2.

Table 2 : Values of RI corresponding to different orders (Source Alonso & Lamata (2006))

D	RI	D	RI	D	RI	D	RI	D	RI
3	0.5247	6	1.2479	9	1.4499	12	1.5365	15	1.5838
4	0.8816	7	1.3417	10	1.4854	13	1.5551		
5	1.1086	8	1.4057	11	1.5140	14	1.5713		

The consistency of an array of comparisons is measured from the reason of consistency *CR*, given by: $CR = CI/RI$

The limit value for *CR* proposed by Saaty (1977) is 0.1. An array of comparisons with CR > 0.1 should have their comparisons reviewed looking for a better consistency.

2.3 Background

It is believed that a sustainable system considers all three types of assessment criteria (i.e. environmental, economic, and social) and maximizes the benefits of each. Over the last two decades various researchers have been trying to promote a sustainable transportation modeling/assessment framework which is discussed in this section.

2.3.1 Linkages-based framework

Jeon and Amekudzi (2005) categorized the frameworks found in literature for measuring progress towards sustainability into linkage-based frameworks. PSR (Pressure-State-Response) is a widely used linkage-based framework (Figure 8). This framework captures the relationships between causal factors (which exert pressures), impacts (change in state) and corrective actions (response).

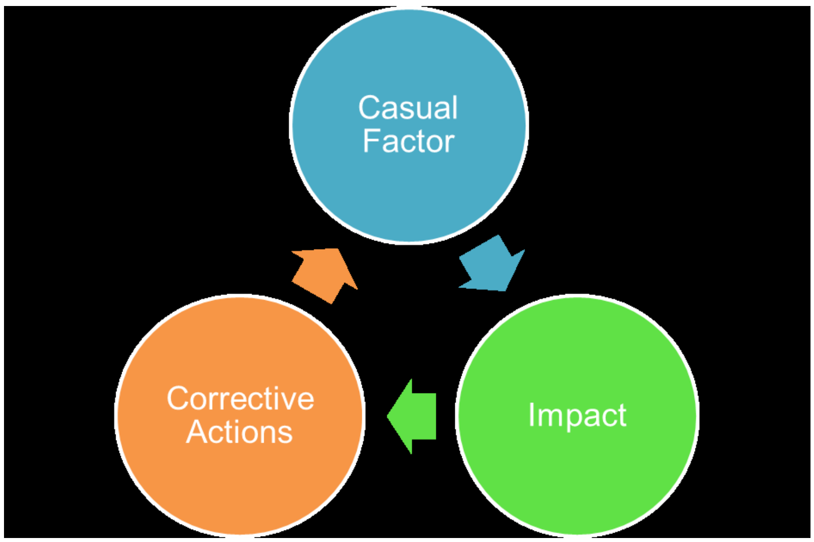

Figure 8: Pressure-State-Response Framework

For example, in order to reduce congestion, an agency may decide to either construct a new road or widen the existing road or use a reserved lane during peak hour. Using this framework one can identify which of the proposed alternatives is sustainable. This can be done by measuring the pressure (e.g. pollution emissions or land use impact), changes of the state (e.g. changes in ambient pollutant levels, habitat diversity, natural resources), and probable responses (e.g. actions, policies, program, changes in awareness and behavior) to prevent, reduce or mitigate the negative impacts associated with each alternative and by comparing the alternatives with each other. One of the drawbacks of this framework is that it only gives qualitative assessment of sustainability. Furthermore, this framework can only be used for comparative sustainability analysis.

2.3.2 Impact-based framework

According to Jeon and Amekudzi (2005), an impact-based framework measures the effectiveness and efficiency with respect to the effects of the transportation system on the economy, the natural environment, and the perceived general social well-being. The tripartite framework is an example of impact-based framework (Figure 9). For example, Transport Association of Canada (TAC) proposed the use of a three dimensional assessment framework corresponding to the three sustainability criteria: environmental - focusing on limitation of emissions and waste; social – with emphasis on equity, human health and quality of life (QOL); and economic – contribution of transportation to the strengthening and diversification of the economy.

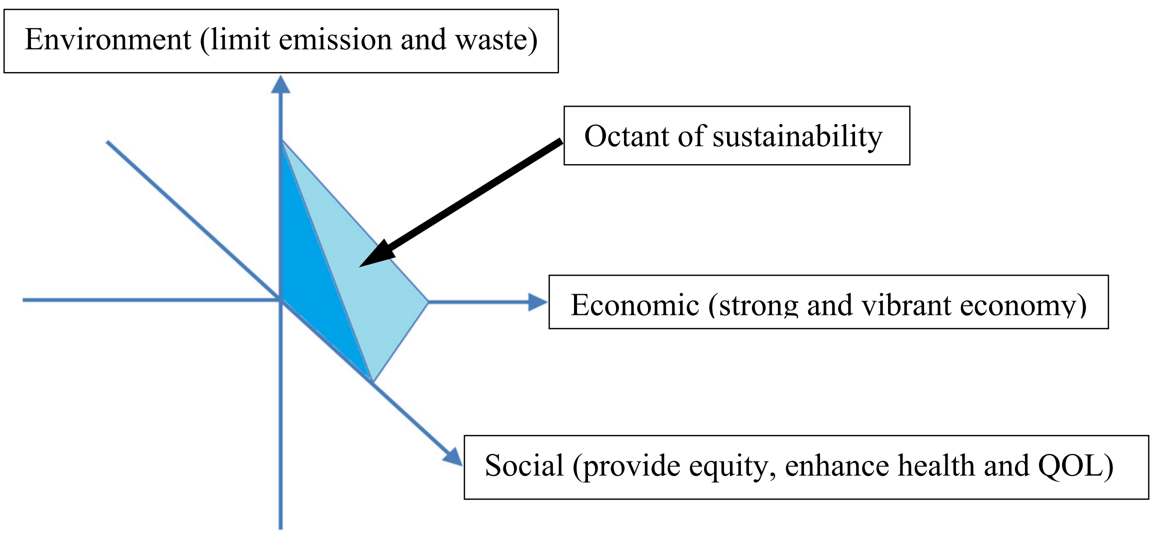

Figure 9: The Tripartite Framework

By setting limits in each of the three dimensions, TAC constructs an optimal octant and any measure that makes the transportation system falls in the octant is sustainable. The limitation of this framework is that it does not specify the way to set limits in each of the three dimensions and provides the means to measure the sustainability of a transportation system. However, many organizations use their own assessment methodology which is customized for local conditions and there is no single standard framework for evaluating progress toward sustainability.

2.3.3 Reductionist approach and comprehensive approach

Litman and Burwell (2006) propose that sustainable transportation can be solved by two approaches. One of that is *reductionist approach* - considering sustainability as a set of individual problems that can be addressed using existing transportation planning models. The main ideology of this approach is that experts rank problems and solutions. For example to achieve economic sustainability one of the sustainability objectives is to increase consumer's mobility and related transportation objectives are to insure adequate transport services and reduce traffic congestion. This transportation objective can be fulfilling by providing adequate road capacity and transit services, improving walking and cycling environment. The other approach is the *comprehensive approach*, which considers sustainability as an integrated problem that cannot be solved using existing single transportation decision–making practice, rather a comprehensive plan (e.g. mixed land use/community design, demand management, traffic calming, congestion pricing etc.) is required. In this study, Litman and Burwell viewed sustainability as a problem solving tool instead of viewing it as an integrated analysis considering large sets of indicators from environmental, social and economic sectors.

2.3.4 Goal-oriented framework

Ramani et al. (2011) described a Goal-oriented framework to evaluate sustainability (Figure 10). The authors explain that in the first step of the evaluation process, one needs to set a goal (e.g. to reduce congestion). The second step is to find a related sustainability planning objective (e.g. congestion management and mitigation), the third step is to find a corresponding indicator (e.g. VMT), the fourth step is to measure the performance (e.g. travel-time index and buffer index) and the final step is using the above performance measure for both the current and the future conditions.

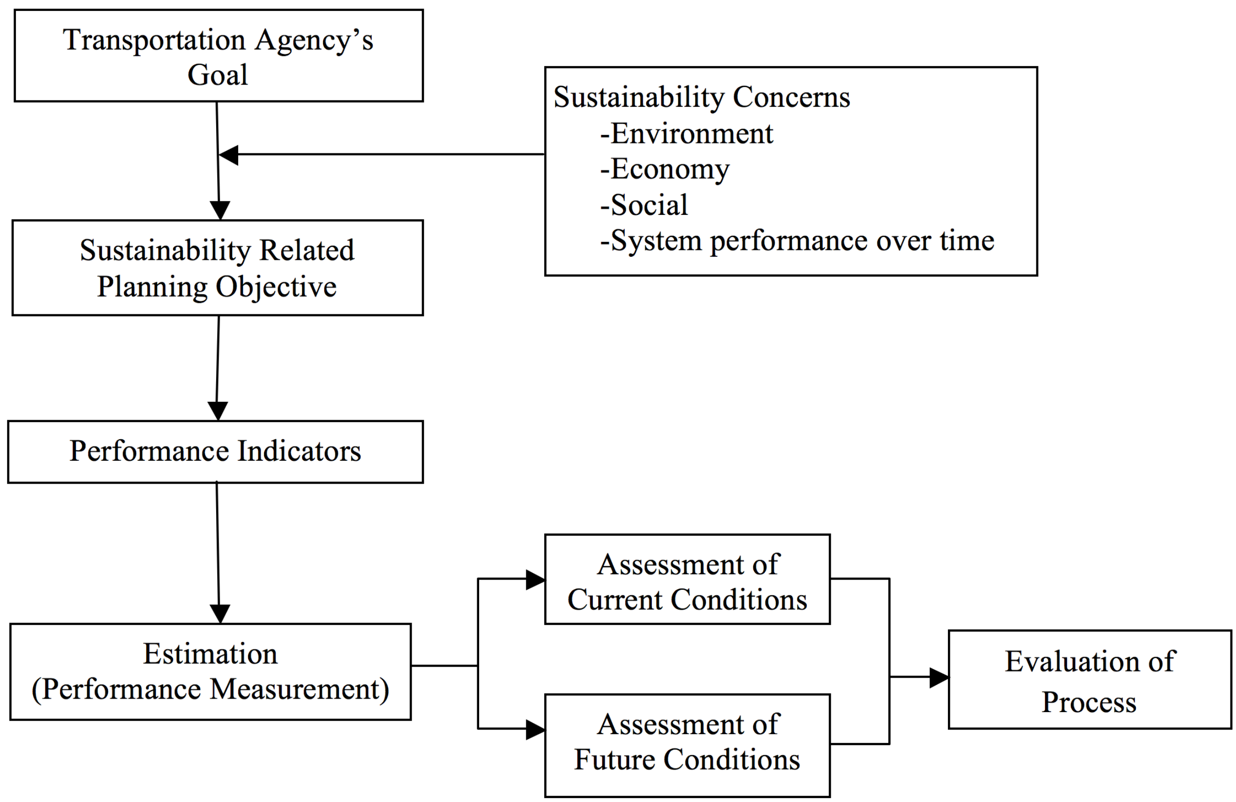

Figure 10: Goal-oriented framework

The major limitation of this framework is that it does not capture the possible interdependence between various goals. For example, if one of the goals is to reduce congestion and another goal is to expand economic opportunity, then this model focuses only on one goal at a time. It does not capture the mutual impact of goals i.e. the way congestion reduction (goal 1) expand economic opportunity (goal 2). Using an analytic hierarchy process, we overcome this problem partially because this process considers the mutual impact of elements in a particular level directly and mutual impact of elements in different levels indirectly.

2.3.5 The Sustainability Footprint model

Amekudzi et al. (2009) introduce a three dimensional X-Y-Z space model called the sustainability footprint (SF) model to evaluate sustainability where in time t_1 a city is located at point $P_1(x_1, y_1, z_1)$ and in time t_2 at point $P_2(x_2, y_2, z_2)$, based on these two features, the sustainability footprint model of that city, $SF = dz_{2-1} / (dx_{2-1} * dy_{2-1})$.

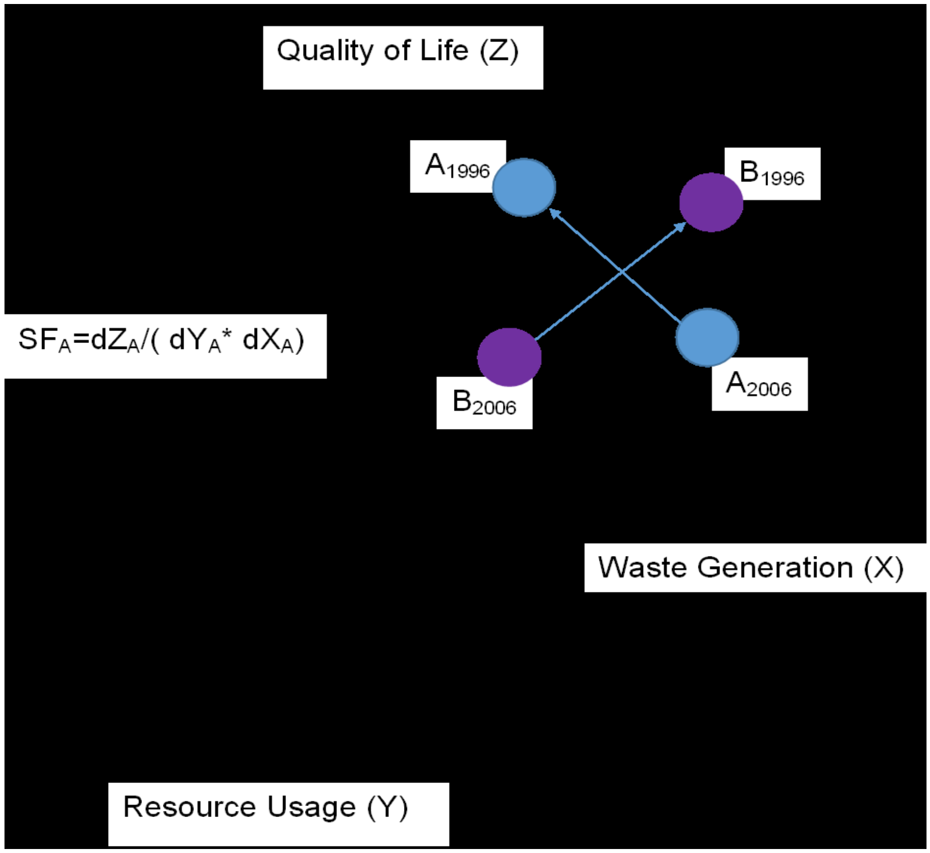

Figure 11: Sustainability Footprint model

For illustration this model could captures the rate of change of an indicator (e.g. community's quality of life (Z-axis)) contributed by a transportation related activity (e.g. the highway network) as a function of two other indicators (e.g. waste generation (X-axis) and resource usage (Y-axis)) (Figure 11). If this rate of change is positive, in case of QOL it can be concluded that the transportation activity generates an improvement in sustainability. Main flaws of this framework is that in this model, one can only identify whether certain decisions lead to or fail to lead to sustainability of a transportation system. Moreover, this model only captures relative sustainability among three entities.

2.3.6 Bottom-up factor oriented framework

Richardson (2005) proposes a bottom-up framework for the analysis of sustainability of both passenger transportation and freight trucking by the synthesis of the information provided by literature search, three discussion groups, and a survey. In this study the author identifies five core indicators at the bottom layer (Figure 12) that influence sustainability. These include fuel consumption, accessibility, congestion, emissions, and safety. Each indicator is influenced by a wide range of factors that influence (i.e. the second layer from the bottom in Figure 12). The factors that influence those factors are at the third layer from the bottom, and it continues like this until it reaches the top layer which is the primary influencer of sustainable transportation. The frameworks show multiple layers of passenger-related and freight-related factors influencing transportation sustainability and their interrelationships which help the policy makers by providing tradeoff among the indicators. The limitation of this framework is that it shows too many inter-relationships which are difficult to analyze. Moreover, it is not suitable for analyzing a large number of indicators.

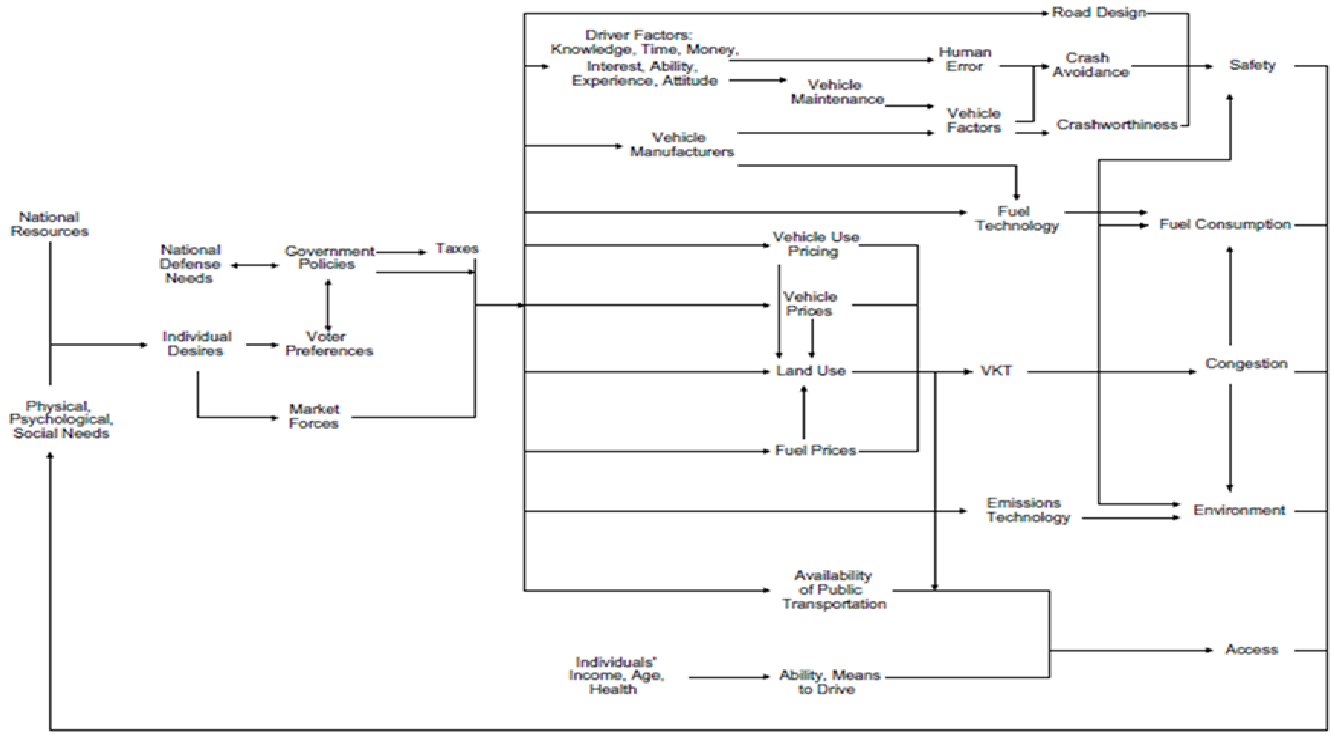

Figure 12: Bottom-up factor oriented framework

2.3.7 Socially sustainable urban transportation model

Boschmann and Kwan (2008) suggested that socially sustainable urban transportation can be achieved by two approaches. One is the place - based accessibility approach, and the other is the individual accessibility approach. In the place based accessibility approach, the relative importance of a place is linked to its accessibility to opportunities related to fundamental human needs. To determine travel pattern, this approach assumes homogeneity of opportunity distribution and travel behavior of individuals within a geographic space. On the other hand in the individual accessibility approach, opportunities to an individual are determined based on disaggregated data at the individual level. To determine travel pattern, this approach uses individual activity and opportunity sets (e.g. individual characteristics, personal constraints, household structure etc.).

From this section we identified that some studies focused on customized solutions for local condition [e.g. Jeon and Amekudzi, (2005)], while other studies investigated transportation sustainability as a problem - solving tool instead of approaching it via an integrated analysis and using extensive sets of performance measures [e.g. Litman and Burwell (2006), and Amekudzi et al. (2009)]. Yet, another group of studies attempted to treat specific objectives separately [e.g. Ramani et al. (2011) and Richardson (2005)], and yet another study focused on achieving just a part of sustainability (Boschmann and Kwan 2008).

2.4 Problem Statement

The review of literature shows that most authors tend to evaluate sustainability of a transportation system by focusing on a specific assessment objective and a comprehensive transportation sustainability analysis framework with a large set of indicators as well as quantification of transportation sustainability. This is an area that needs to be further investigated.

The present study proposes a comprehensive modeling framework in the form of a hierarchical diagram to evaluate quantitatively the sustainability of transportation systems in a systematic and rational way. It is a top-down framework with the broadest goal at the top level (sustainable transportation). Different layers of details spread down the diagram through different objectives and sub-objectives, until they reach specific attributes. The last layer in the proposed diagram introduces indicators and performance measures that are attached to individual attributes.

CHAPTER 3

METHODOLOGY

Comprehensive transportation sustainability analysis is divided into two parts. The first part deals with the development of the hierarchy diagram as an assessment framework and the second part deals with the analysis of the hierarchy diagram. This study deploys analytic hierarchal process as the analysis tool.

3.1 Assumptions

The proposed framework is based on the following assumptions

- Indicators obtained from literature search are assumed to be valid and effectively capture the purpose of attributes.
- The impacts of different measuring units in indicator measurement are assumed to be considered during the pair wise comparison in AHP.

3.2 Proposed Sustainability Assessment Framework

After careful assessment of the above indicators and grouping, this study proposes a methodology to assess the sustainability of a transportation network in the form of a comprehensive and flexible system assessment framework. The modeling framework is based on balancing a set of sustainability objectives related to environmental, social and economic criteria, respectively.

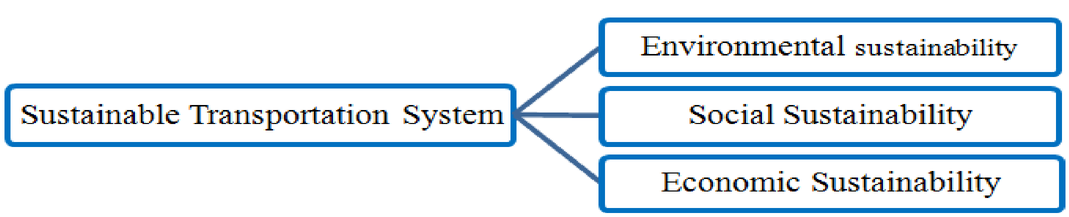

Figure 13: Framework for sustainable transportation

The proposed framework has ***three steps*** as follows**.** ***First***, a literature review is performed to identify the sustainability indicators with measuring units and to group them into three types. Table 3 shows the most frequently used sustainability indicators.

Table 3 : Indicators and their measuring units related to three major characteristics

	Indicators [Measuring Unit]	
Environmental	Others vehicle emissions (HC, CO, NO_x, PM, SO_x, VOC & Toxic subs) (Air quality index) [*Grams/mi/day*]	Preservation of wildlife habitat (wetlands, forests) [*%protect area*]
	Non-renewable non-recyclable resource (fossil fuel) use [*liters/person/y*]	Non-renewable recyclable resource (mineral) use
	Water pollution [*Per capita vehicle fluid losses*]	Low emission vehicles purchased [*% / y*]
	Per capita gas use vs. urban density [m^3*/prs/y/ density*]	Fuel efficiency [*ton-miles/gallon*]
	Releases of deicing chemicals, & cleaning fluids[*tons/y*]	Impervious surfaces [*% or* $mile^2$]
	GHG emissions (CO_2, CH_4, N_2O, O_3) [*gms* CO_2*/mi/day*]	Waste/Recycling [*%*]
	Per capita land devoted to transportation facilities[$mile^2$]	Alternative fuel use
	Storm water treatment [*% roads under treatment*]	
Social	Degree to which non-motorized transport consider [*%*]	Degree to which prices reflect full costs [*%*]
	Quality of pedestrian and bicycle environment [*Scoring*]	Intensity of interactions among neighbors
	Crash disabilities and fatalities [*crashes/*10^6 *population*]	HH expenditure on transportation [*%*]
	Population exposed to high levels of traffic noise [*%*]	Car ownership [*Vehicle/1000 people*]
	Bus fleets/ rail station compliant with disable act [*%*]	Accidental deaths [*No/*10^6*VKT /y*]
	Satisfaction rating of transport system [*Scoring*]	Animal / wildlife collisions [*Number/y*]
	Population using non- motorized transport [*%*]	Road length having footpath [*%*]
	Severe crashes [*crashes/100*10^6 *vehicle-miles*]	Accessibility or Universal design
	Time to the next public transport stop [*min*]	Income inequality [*Gini index*]
	Road length with double or more lanes [*%*]	Time to get to work place [*min*]
	Traffic monitoring coverage [*%lane-mile*]	Citizen involvement
	Time devoted to recreational travel [*min*]	Potholes [*Number/km*]
Economic	Degree to which planning reflect least-cost & investment practices [*Cost/Benefit ratio*]	Quality of non-automobile modes relative to auto
	Average pavement condition (Distress, Rutting, Ride quality) [*Scoring*]	Per capita expenditures devoted to transport [*%*]
	Impact on employment [*Emp. to people. ratio in CBD*]	Commuters using Public Transport [*%*]
	Per capita short journeys per year by mode [*billions / %*]	Portion of Public Transport in total [*%*]
	Mode split (walking, cycling, rideshares and transit) [*%*]	Average commute travel time [*min*]
	Change in level of road congestion over time [*B.I., %*]	Quality of public transport [*Scoring*]
	Per capita PKT or VKT - by mode, purpose & category	Per capita congestion costs [*$/km*]
	Throughput efficiency– by category [*Veh-mi/h/lane*]	Average speed of transport [*km/h*]
	Portion of Rail commuters in public transport [*%*]	Contribution towards GDP [*%*]
	Peak hour auto occupancy to/from CBD [*No Dimension*]	Load factors for transport [*%*]
	Proportion of non-single occupant travel [*% PMT*]	Travel-time index [*No Dimension*]
	Annual travel occurs in congested conditions [*%*]	Per capita road length [*meter*]
	Avg. home-work trip distance/time [*km or min*]	

However, oftentimes transportation analysts add or remove indicators according to the specific needs that are based on quality and availability of data. Also, more precise information could be obtained by dividing an indicator into multiple parts. For example, per capita VKT (vehicle-km travelled) is a generally accepted indicator strongly correlated to demand for travel. But, additional information regarding travel demand can be obtained by using the discretized indicator of per capita PKT (person-km travelled) by mode. Additionally, dividing the demand for travel by its purpose and category, a better insight about travel behavior can be inferred.

The second step of the proposed methodology proposes hierarchal diagram to evaluate the overall level of sustainability by determining the relative impact of individual indicators on each of the three types of sustainability objectives, environmental, social and economic, respectively. For example, the ultimate objective of the environmental sustainability is to protect the climate and to maintain an environmental stability. With respect to the transportation impact, pollution prevention and land use development are estimated to be the major factors contributing to climate protection. Different studies recognized that the environmental stability is affected by specific transportation activities, directly or indirectly. Regardless of these negative impacts, it is commonly accepted that it can be reversed by changing our focus on conservation of natural resources (e.g. reduction of fossil fuel, development of renewable energy sources, etc.). To conduct a comprehensive environmental transportation sustainability analysis, the indicators are grouped into categories based on specific objectives, sub-objectives and attributes (means to achieve sub-objectives) as shown in Figure 14 and in Table 4.

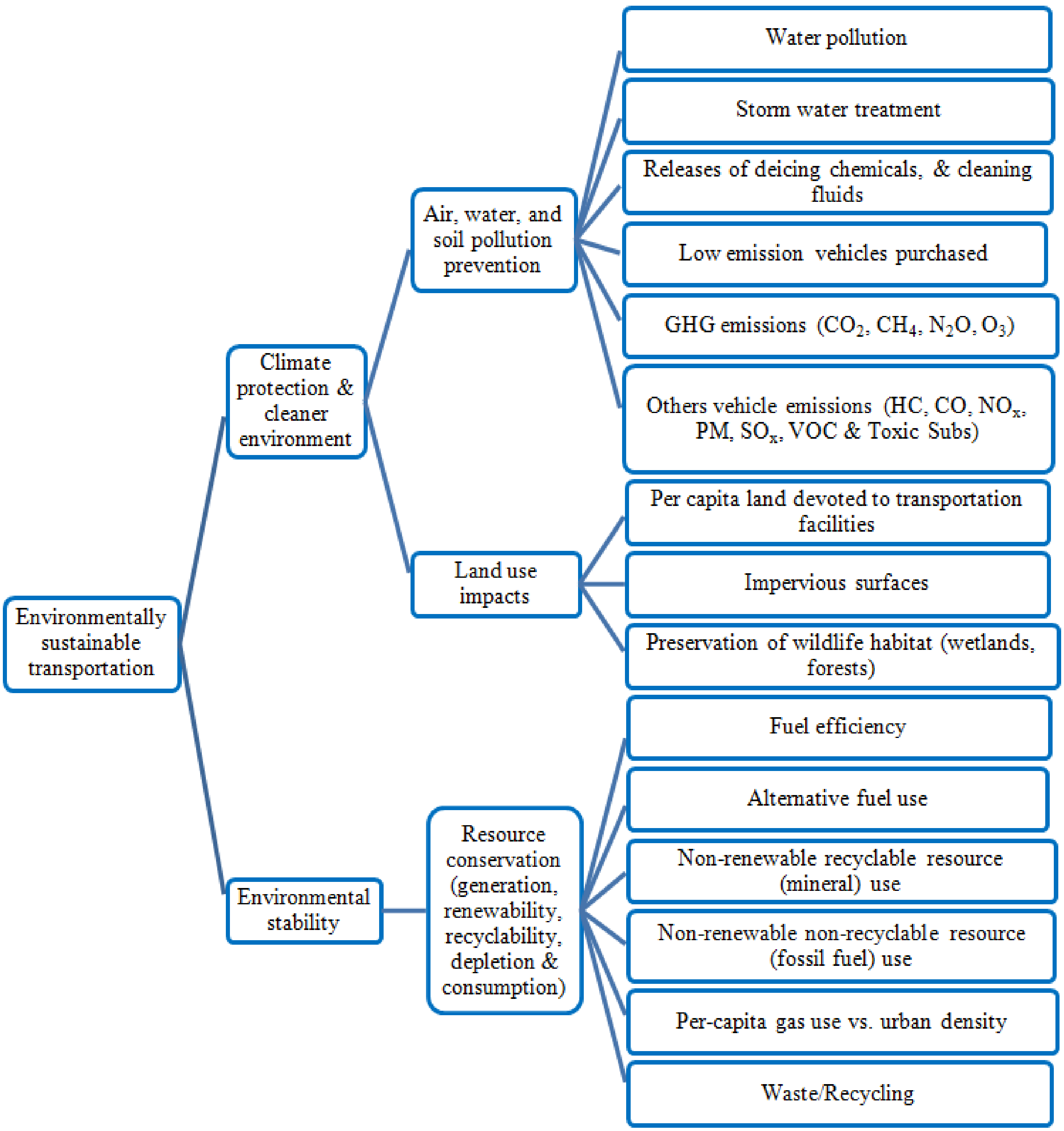

Figure 14: Environmental sustainability

Table 4 : Grouping of environmental sustainability indicators

Objectives	Sub-objectives	Attributes	Indicator	Unit
Environmental sustainability	Climate protection & cleaner environment	Air, water, and soil pollution prevention	Water pollution	Vehicle fluid
			Storm water treatment	% Roads treated
			Releases of deicing chemicals, & cleaning	Tons/y
			Low emission vehicles purchased	% / year
			GHG emissions (CO_2, CH_4, N_2O, O_3)	Gms CO_2/mi/d
			Others vehicle emissions (HC, CO, NO_x, PM, SO_x, VOC & Toxic subs) (Air quality index)	Gms CO_2/mi/d
		Land use impacts	Per capita land devoted to transportation	$mile^2$
			Impervious surfaces	% or $mile^2$
			Preservation of wildlife habitat (wetlands,	% protect area
	Environmental stability	Resource conservation (generation, renewability, recyclability, depletion and consumption)	Fuel efficiency	ton-miles/gal
			Alternative fuel use	
			Non-renewable recyclable resource (mineral)	
			Non-renewable non-recyclable resource (fossil fuel) use	liters/person/y
			Per-capita gas use vs. urban density	m^3/prs/y/density
			Waste/Recycling	%

Similarly, it is commonly agreed that proper transport planning, enhancing safety, increasing cohesion and livability, improving health and fitness and providing equity are major concern in social sustainability. Appropriate transport planning can be achieved by applying universal access design principles to new or existing transportation facilities (e.g. providing public transportation accessible to all regardless of age or physical abilities), by citizen involvement (i.e. public input) and by non-motorized transport planning. Transportation safety can be enhanced by ensuring better road surface condition, by crash prevention and protection, as well as by improving incident detection and response. Cohesion and livability might be increased by enhancing public territory (e.g. acquisition of right-of-way), by improving local environmental quality (e.g. creating or rebuilding damaged green spaces), and by accessibility to recreational places. Health and fitness could be improved by encouraging non-motorized transport and by reducing noise pollution. Equity could be achieved by improving accessibility, by providing horizontal equity (e.g. price of monthly pass is the same for all groups of people regardless of race, gender or income group) and vertical equity (e.g. users with more ability to pay should pay more for monthly pass), by removing social disparity (e.g. highways may provide most of the services to private vehicle users if public transport is not developed concurrently) and by providing affordable transportation services in general. In order to conduct a comprehensive transportation analysis using the social sustainability criterion, the specific indicators are grouped into categories based on specific objectives, sub-objectives and attributes as shown in Figure 15 and in Table 5.

Finally, increasing economic efficiency and improving consumer's mobility is expected to contribute to the economic sustainability of transportation systems. The economic efficiency of a transportation system could be achieved by increasing macro-economic contribution, by preserving the value of transportation infrastructure (e.g. proper maintenance scheduling and repairs), by improving freight facilities (e.g. minimize freight transfer at intermodal nodes) and by service efficiency. Consumer's mobility could be improved by ensuring affordability, by increasing public transport, by providing adequate capacity to satisfy the demand, by reducing congestion and by improving public transport reliability. To conduct a systematic economic transportation sustainability analysis, the relevant indicators are grouped into categories based on specific objectives, sub-objectives and attributes as shown in Figure 16 as well as in Table 6. In ***the third step*** the analytic hierarchy process is used to determine a global sustainability index as explained in the following section of this thesis.

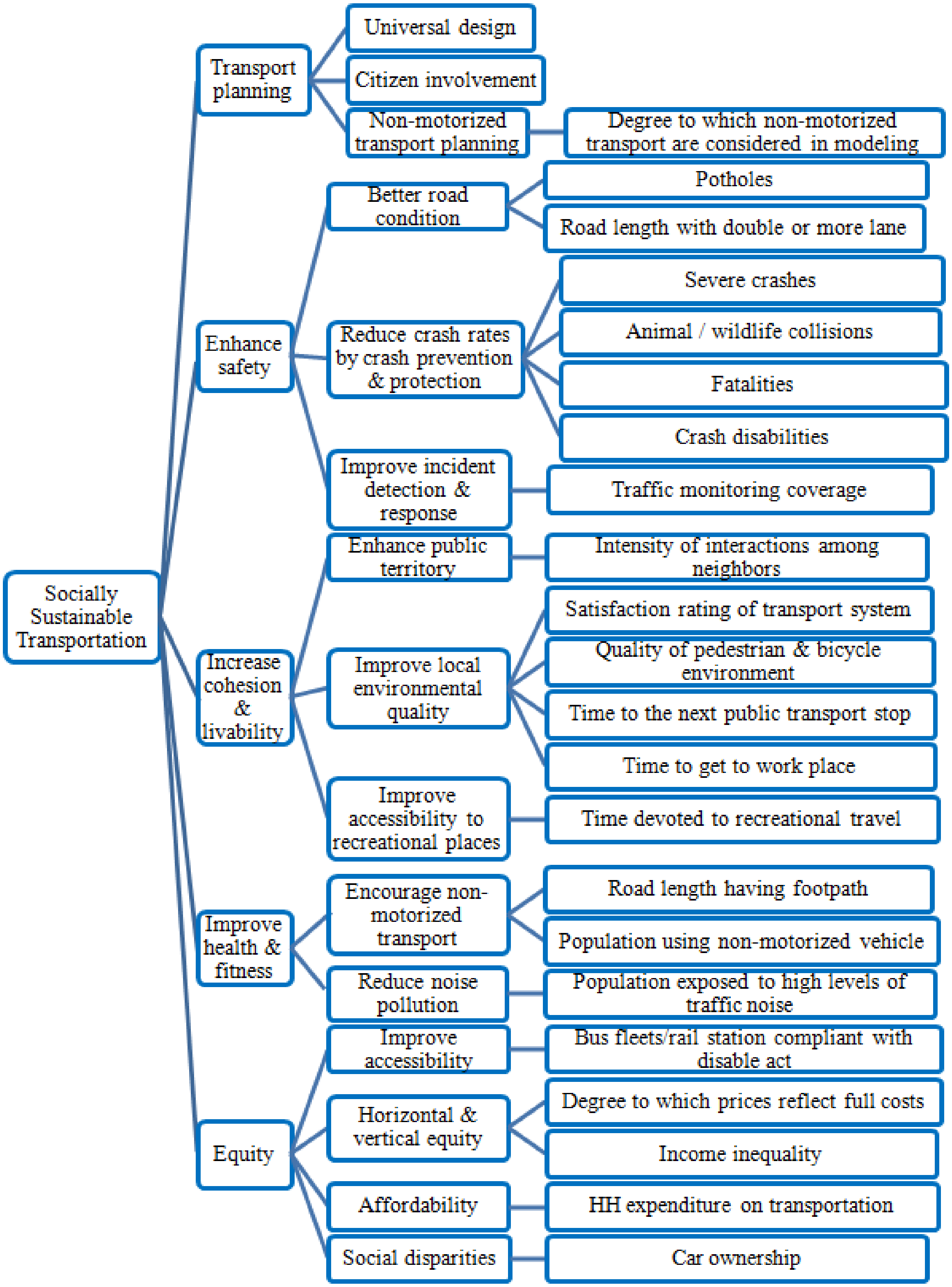

Figure 15: Social sustainability

Table 5 : Grouping of social sustainability indicators

Objective	Sub-objectives	Attributes	Indicator	Unit
Social sustainability	Enhance safety	Better road condition	Road length with double or more lanes	%
			Potholes	Number/km
		Reduce crash rates by crash prevention and crash protection	Fatalities	Number/10^6VKT /y
			Crash disabilities	Crash/10^6people
			Severe crashes	Crashes/100million veh-mi
			Animal / wildlife collisions	Number/y
		Improve incident detection & response	Traffic monitoring coverage	% lane-mile
			% of road length having street lighting	
	Increase cohesion and livability	Improve local environmental quality	Satisfaction rating of transport system	Scoring
			Quality of pedestrian and bicycle	Scoring
			Time to the next public transport stop	min
			Time to get to work place	min
		Enhance public territory	Intensity of interactions among neighbors	
		Improve accessibility to recreational places	Time devoted to recreational travel	min
	Imp. Health and fitness	Improve walking, and cycling conditions, encourage non-motorized transport.	Road length having footpath	%
			Population using non- motorized transport	%
		Reduce noise pollution	Population exposed to high levels of traffic noise	%
	Equity	Improve accessibility	Quality of accessibility and transport	
			Bus fleets/ rail station compliant with	%
		Horizontal and vertical equity	Degree to which prices reflect full costs	%
			Income inequality	Gini index
		Affordability	HH expenditure on transportation	%
		Social disparities	Car ownership	Veh./1000 people
	Transport planning	Universal design		
		Citizen involve		
		Non-motorized transport planning	Degree to which non-motorized transport are considered in modeling	%

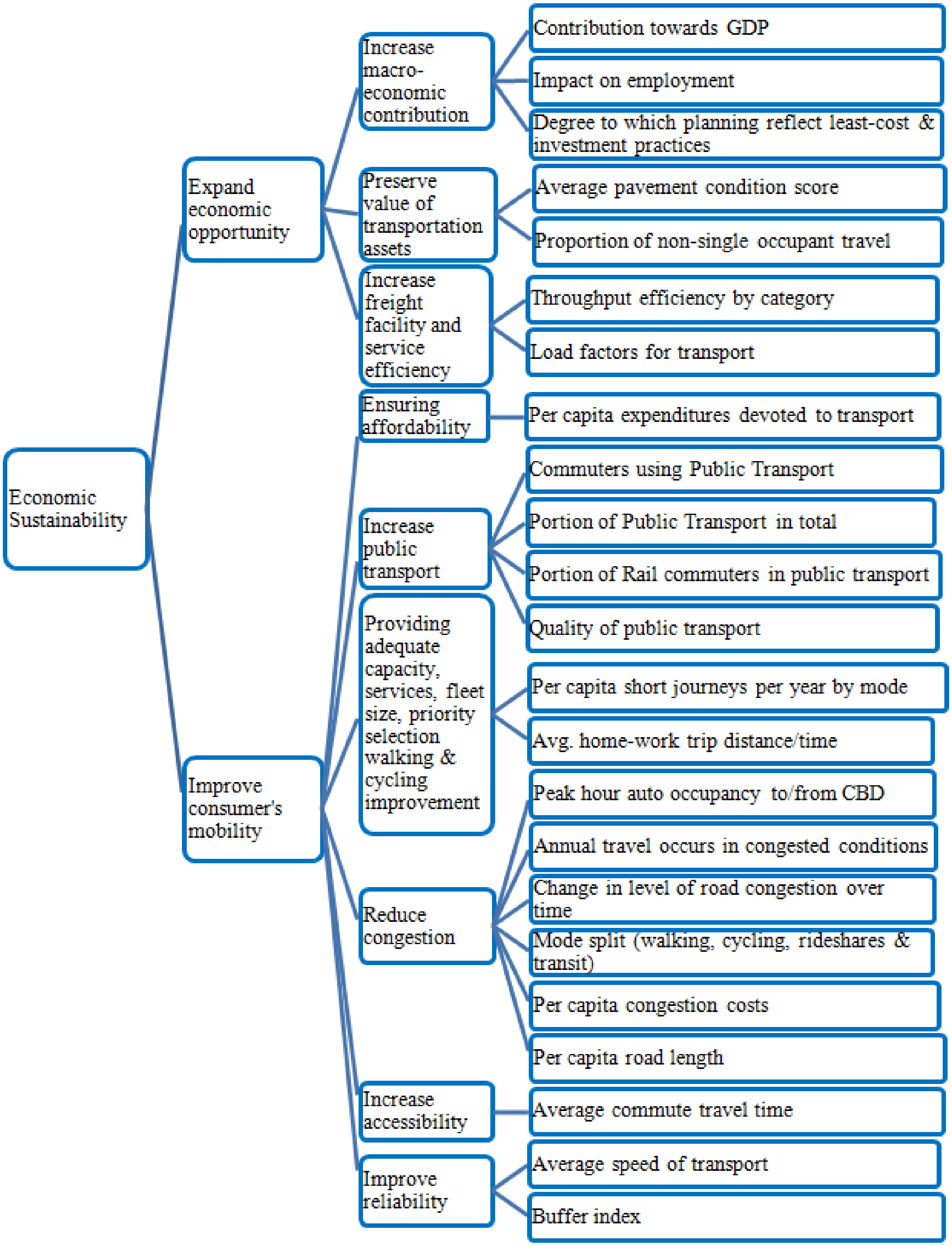

Figure 16: Economic sustainability

Table 6 : Grouping of economic sustainability indicators

Objective	Sub-objectives	Attributes	Indicator	Unit
Economic Sustainability	Increase economic efficiency	Increase macro-economic contribution	Contribution towards GDP	PPP
			Impact on employment	Employment to population ratio
			Degree to which planning reflect least-cost	No Dimension
		Preserve value of transportation assets	Proportion of non-single occupant travel	% PMT
			Average pavement condition score (Distress, Rutting, Ride quality)	No Dimension
		Improve freight facility and service efficiency	Truck throughput efficiency	Truck-mi/h/lane
			Load factors for freight transport	%
	Improve consumer's mobility	Ensuring	Per capita expenditures devoted to transport	%
		Increase public transport	Commuters using Public Transport	%
			Portion of Public Transport in total	%
			Portion of Rail commuters in public transport	%
			Quality of public transport	Scoring
		Providing adequate capacity, services, fleet size, priority selection walking and cycling improvement	Per capita PKT or VKT - by mode, purpose & category	
			Per capita short journeys per year by mode	Billions or %
			Avg. home-work trip distance/time	km or min
		Reduce congestion	Peak hour auto occupancy to/from CBD	No Dimension
			Annual travel occurs in congested conditions	%
			Change in level of road congestion over time	Buffer index, %
			Per capita road length	meter
			Road Utilization Index (RUI)	
			Vehicles per road length – by category	
			Mode split (walking, cycling, rideshares & transit)	%
			Per capita congestion costs	$/km
		Improve reliability	Average speed of transport	km/h
			Travel-time index	No Dimension
		Increase accessibility	Average commute travel time	min

3.3 Analysis

To construct the comparison matrices in indicator level or to rank the indicator, this study considers the adjusted R^2 and F-statistics value obtained from ANOVA by SPSS software. Data to prepare analysis of variance of indicators are taken from CANSIM table. In case of indicators data unavailability, the ranking of 1 is assumed. To prepare comparison matrices for objectives, sub-objectives and attributes, this study considers equal importance for every entity. Another option is to build comparison matrices for objectives, sub-objectives and attributes is to consider experts opinion. Table 10 is the finale output of AHP analysis. The detailed AHP analysis is attached in the appendix A, B, C.

As in the subjective comparison matrix we consider equal importance on economic, environment and social sustainability it is evident from first level of Table 10 that all the component has 33.33% impact on achieving sustainable transportation system. Similarly, if we observe the second level, it reveals that all sub-objectives have equal impact on related objective because in the subjective comparison matrix we consider equal importance of all sub-objectives to achieve the related objectives. Same phenomenon repeated in the third level. We consider equal importance in the subjective comparison matrices related to objectives, sub-objectives and attributes because data for analysis is not available in these level.

For the bottom level or indicator level we collect data from Canadian socioeconomic database (CANSIM) and perform statistical analysis using SPSS software. SPSS output for environmental indicators, social indicators and economic indicators are shown in Table 7, Table 8, and Table 9 respectively. Forth column of these tables shows value of F – Statistics which in fact is the ratio of between – group variability and within-group variability. The greater the value of F – Statistics, the more is the variability in between group compared to within group. In other word the more is the value of F – Statistics, the worse it is to achieve sustainability. Therefore, in such case, we consider higher score in the last column in Table7. Table 8 and Table 9. Fifth column shows adjusted R^2 value which provides a measure of how well observed outcomes are replicated by the model. The value of this ranges from 0 to 1. The better the linear regression the closer the value of R^2 is to one. The last column of each of Table 7, Table 8, and Table 9 reflect the ranking we consider, depending on the value of F - Statistics and adjusted R^2. Ranking scale is chosen from 1 to 10 where 1 represents least important and 10 represent most important. This ranking is used to construct subjective comparison matrices in AHP. The column leveled as "Final weight of each indicators" in Table 10 represents the ultimate importance that a particular indicator has on achieving transportation sustainability. This weight is the output of the theoretical analysis. From this weight we could identify the indicators which have significant impact on achieving transportation sustainability. The column of "value attributed to each indicator" represents the current status of an indicator for a particular transportation system that is to be assessed. The value assign to this column on a scale will be used to evaluate and determine the sustainability index of a transportation system. For illustration, we choose first indicator of the each third level grouping as 10 and rest are 5, where 10 represent excellent condition, 1 represents worst condition and 5 represent average condition. Using this value we obtain the Sustainability Index (SI) of the system which is 5.95 shown at the bottom of Table 10. To chive this index, the contribution of economic sustainability is 6.59 (Appendix B), the contribution of environmental sustainability is 5.62 (Appendix C), and the contribution of social sustainability is 5.79 (Appendix D).

The most significant of the framework listed above is that it quantifies the achievement of sustainability and identifies the important focus areas depending on subjective input of comparison matrix. Additionally, this framework can also be used to evaluate the sustainability of an entity by calculating the sustainability index.

Table 7: ANOVA for Environmental Sustainability from SPSS result

Environmental Sustainability

Indicator	CANSIM SOURCE	No of Observations	F_0	Adj. R^2	β_0	Sig. (β_0)	β_1	Sig. (β_1)	Scoring out of 10
Low emission vehicles purchased	Table 405-0004	12	44.33	0.83	-0.61	0.39	1.18	0.03	3
Alternative fuel use	Table 153-0014	21	19.82	0.92	3.16	0.00	-0.67	0.00	1
Per capita gas use	Table 131-0001	277	3212.92	0.98	-2.03	0.00	0.03	0.00	9
Fossil fuel use	Table 126-0001	278	3212.92	0.98	-1.83	0.00	0.02	0.00	9
Mineral use	Table 405-0003	228	326.20	0.98	-1.50	0.00	0.02	0.00	3
GHG emissions	Table 153-0033	19	661.30	0.98	1.49	0.00	-0.02	0.80	6

Table 8: ANOVA for Social Sustainability from SPSS result

Social sustainability

Indicator	CANSIM SOURCE	No of Observations	F_0	Adj. R^2	β_0	Sig. (β_0)	β_1	Sig. (β_1)	β_2	Sig. (β_2)	Scoring out of 10
Crash disabilities and fatalities	Table 409-0003	23	0.48	0.06	-0.61	0.37	0.19	0.16	-0.01	0.11	9
Severe crashes	Table 409-0003	23	1.42	0.07	-0.32	0.63	0.15	0.26	-0.01	0.15	9
Accidental deaths	Table 409-0003	23	4.21	0.29	-0.36	0.54	0.20	0.09	-0.01	0.03	9
Bus fleets compliant with disable act	Table 405-0004	23	68.54	0.53	-2.47	0.00	0.74	0.00	-0.06	0.01	7
Time devoted to recreational travel	Table 405-0025	14	0.83	0.58	0.53	0.03	-0.30	0.03	0.05	0.02	5
Satisfaction rating of transportation system	Table 409-0001	23	8.01	0.64	3.05	0.00	-0.71	0.00	0.04	0.05	5
Income inequality	Table 079-0003	279	5.86	0.83	-1.09	0.00	0.00	0.05	0.00	0.00	3
Car ownership	Table 405-0014	5	11.98	0.98	-0.39	0.52	-0.62	0.45	0.34	0.33	5

Table 9 : ANOVA for Economic Sustainability from SPSS result

Economical Sustainability

Indicator	CANSIM SOURCE	No of Observations	F_0	Adj. R^2	β_0	Sig. (β_0)	β_1	Sig. (β_1)	Scoring out of 10
Peak hour auto occupancy to from CBD	Table 405-0074	10	3.83	0.41	1.87	0.26	-2.10	0.11	6
Change in level of road congestion over time	Table 405-0029	38	7.70	0.52	-0.68	0.02	0.06	0.39	6
Annual travel occurs in congested conditions	Table 405-0028	38	0.37	0.54	-1.87	0.00	0.38	0.00	6
Contribution towards GDP	Table 402-0001	12	3.74	0.67	0.93	0.15	-0.66	0.01	6
Per capita short journeys	Table 405-0051	13	0.01	0.68	-0.33	0.52	0.66	0.05	7
Average home-work trip distancetime	Table 405-0049	13	2.65	0.69	-1.79	0.00	1.15	0.00	7
Impact on employment	Table 408-0007	8	111.65	0.94	-1.79	0.00	0.40	0.00	3
Throughput efficiency	Table 405-0055	10	538.79	0.99	-1.56	0.00	0.21	0.00	5
Degree to which planning reflect least-cost and investment practices	Table 408-0004	124	1067.95	0.99	-1.46	0.00	0.02	0.00	6
Commuters using public transport	Table 405-0092	4	6.28	1.00	7.36	0.00	-8.68	0.00	5
Mode split	Table 405-0093	4	6.23	1.00	7.36	0.00	-8.68	0.00	3
Per capita expenditures devoted to transport	Table 079-0004	4	80.52	1.00	-1.27	0.00	0.13	0.00	7
Portion of public transport in total	Table 079-0004	4	8.18	1.00	5.32	0.00	-5.31	0.00	5

Table 10: Combined sustainable transportation

First level		Second Level		Third Level		Bottom Level		Final Weight of each Indicator	Value Attributed to each Indicator	Final Result per Indicator
Economic sustainability	0.333	Expand economic opportunity	0.50	Increase macro-economic contribution	0.33	Contribution towards GDP	0.200	0.011	10	0.11
						Impact on employment	0.200	0.011	5	0.06
						Degree to which planning reflect least-cost and investment practices	0.600	0.033	5	0.17
				Increase freight facility and service efficiency	0.33	Load factors for freight transport	0.250	0.014	10	0.14
						Truck throughput efficiency	0.750	0.042	5	0.21
				Preserve value of transportation assets	0.33	Ave. pvt. condition score	0.500	0.028	10	0.28
						Proportion of non-single occupant travel	0.500	0.028	5	0.14
		Improve consumer's mobility	0.50	Ensuring affordability	0.17	Per capita expenditures devoted to transport	1.000	0.028	5	0.14
				Increase public transport	0.17	Commuters using Public Transport	0.250	0.007	10	0.07
						Portion of Public Transport	0.250	0.007	5	0.03
						Portion of rail commuters in Public Transport	0.250	0.007	5	0.03
						Quality of Public Transport	0.250	0.007	5	0.03
				Provide adequate services	0.17	Percapita shprt journeys per year	0.500	0.014	10	0.14
						Ave. H-W trip distance	0.500	0.014	5	0.07
				Reduce congestion	0.17	Peak hour auto occupancy	0.300	0.008	10	0.08
						Annual travel occurs in congestion	0.300	0.008	5	0.04
						Change in congestion level	0.300	0.008	5	0.04
						Per capita road length	0.033	0.001	5	0.00
						Mode split	0.033	0.001	5	0.00
						Per capita congestion costs	0.033	0.001	5	0.00
				Increase accessibility	0.17	Average commute travel time (min)	1.000	0.028	5	0.14
				Improve reliability	0.17	Ave. speed	0.500	0.014	10	0.14
						Buffer index	0.500	0.014	5	0.07

Table 11: Combined sustainable transportation (continued)

Environmental sustainability	0.333	Climate protection and cleaner environment	0.50	Air, water, and soil pollution prevention	0.50	Water pollution	0.077	0.006	10	0.06
						Storm water treatment	0.077	0.006	5	0.03
						Release deicing chemicals and cleaning fluids	0.077	0.006	5	0.03
						Low emission vehicle purchased	0.231	0.019	5	0.10
						GHG emissions	0.462	0.038	5	0.19
						Others vehicle emissions	0.077	0.006	5	0.03
				Land use impact	0.50	Per capita land devoted to transport facility	0.333	0.028	10	0.28
						Impervious surfaces	0.333	0.028	5	0.14
						Preservation of wildlife habitat	0.333	0.028	5	0.14
		Environmental stability	0.50	Resource Conservation	1.00	Fuel efficiency	0.042	0.007	10	0.07
						Alternative fuel use	0.042	0.007	5	0.03
						Non-renewable recyclable resource (mineral) use	0.125	0.021	5	0.10
						Non-renewable non-recyclable resource (fossil fuel) use	0.375	0.063	5	0.31
						Per-capita gas use vs. urban density	0.375	0.063	5	0.31
						Recycling	0.042	0.007	5	0.03

Table 12 : Combined sustainable transportation (continued)

Socially sustainable transportation	0.333	Transport planning	0.20	Universal design	0.33		1.000	0.022	5	0.11
				Citizen involvement	0.33		1.000	0.022	5	0.11
				Non-motorized transport planning	0.33	Degree to which non-motorized transport are considered in modeling	1.000	0.022	5	0.11
		Enhance safety	0.20	Better road condition	0.33	Potholes	0.500	0.011	10	0.11
						Road length with double or more lane	0.500	0.011	5	0.06
				Crash prevention and protection	0.33	Severe crashes	0.375	0.008	10	0.08
						Animal/wildlife collisions	0.062	0.001	5	0.01
						Accidental deaths	0.188	0.004	5	0.02
						Crash disabilities and fatalities	0.375	0.008	5	0.04
				Improve incident detection and response	0.33	Traffic monitoring coverage	1.000	0.022	5	0.11
		Increase cohesion and livability	0.20	Enhance public territory	0.33	Intensity of interactions among neighbors	1.000	0.022	5	0.11
				Improve local environmental quality	0.33	Satisfaction rating of transportation system	0.500	0.011	10	0.11
						Quality of padestrian and bicycle environment	0.167	0.004	5	0.02
						Time to next public transport stop	0.167	0.004	5	0.02
						Time to get to work place	0.167	0.004	5	0.02
				Improve accessibility to recreational places	0.33	Time devoted to recreational travel (min)	1.000	0.022	5	0.11
		Improve healty and fitness	0.20	Encourage non-motorized transport	0.50	Road length having footpath	0.500	0.017	10	0.17
						Population using non-motorized vehicle	0.500	0.017	5	0.08
				Reduce noise pollution	0.50	Population exposed to high levels of traffic noise	1.000	0.033	5	0.17
		Equity	0.20	Improve accessibility	0.25	Bus fleets/rail station compliant with disable act	1.000	0.017	5	0.08
				Horizontal and vertical equity	0.25	Degree to which prices reflect full costs	0.333	0.006	10	0.06
						Income inequality	0.667	0.011	5	0.06
				Affordability	0.25	HH expenditure on transportation	1.000	0.017	5	0.08
				Social disparities	0.25	Car ownership	1.000	0.017	5	0.08

***SI* = 5.95**

CHAPTER 4: CONCLUDING REMARKS AND FUTURE WORK

4.1 Summary and Conclusions

For many national and local transportation authorities it became more and more important to develop a comprehensive analysis framework that can be used as a sustainability assessment tool of the transportation infrastructure. This thesis proposes a methodology to assess the sustainability of the transportation systems independent of the scale of the analyzed networks. Basically, the proposed analysis framework shows that while an exhaustive list of sustainability indicators is not necessary, transportation professionals can apply the proposed methodology using the available data for the purpose of identifying an initial sustainability index. As more information can be collected, the initial index can be ameliorated. Using the available data from Statistics Canada and from existing literature a total of sixty-one indicators are proposed to be considered as significant impact factors on the transportation systems' sustainability. The proposed methodology combines the indicators in a hierarchical structure in order to overcome the complexity of dealing with larger sets of indicators. It is proven that the AHP-based method is a suitable analysis tool for this type of data structure. However, to build-up a reliable comparison matrix for AHP model, coordinated decisions among different sectors, groups, and jurisdictions is necessary. Moreover, data for statistical analysis to split the various indicators via objectives, sub-objectives and attributes are not always readily available. As an alternative, expert opinions can be used to build-up a subjective comparison matrix. As a result of the calculation of all comparisons matrices using the AHP model, the final relative weight of each indicator can be determined. Finally, after grading all indicators from the lowest level one can obtain a final sustainability assessment of the whole system.

The proposed framework becomes rigorously structured and conveniently flexible to allow for particular adjustments that suit best local analysis conditions (i.e. the analyst would be able to adjust the overall effect of various indicators on the sustainability of the given transportation system by defining specific importance or weights, in the assessment model). The analyst is given total control to assign the weights for individual indicators to the extent that some indicators may be removed, and/or new factors may be added. The effectiveness of this framework depends on the inclusion of appropriate indicator and use of expert opinion during building comparison matrix. To recap, the following represents the contribution of this thesis:

- Is provides a comprehensive sustainability assessment framework by considering a large sets of indicators.
- The proposed methodology overcomes the complexity analyzing large sets of indicators by using a hierarchical diagram.
- The application of this tool helps to quantify the level of transportation sustainability of a given infrastructure and identifies the focus areas that have the bigger influence.
- The propose methodology can be used to evaluate the sustainability of an existing of developing transportation system by associating a corresponding sustainability index.

Once a sustainability measure is defined, one can use it to develop a specification limits for various impact factors that affect sustainability. These limits can be determined independently for different components of the sustainability index (i.e. economic, social, and environmental). Finally, the development of specification limits for various indicators can contribute to propose specific guidelines that contribute to ameliorate the sustainability of the transportation systems in general.

4.2 Future work

One of the limitation of this thesis is that it assumes equal importance of objectives, sub-objectives and attributes in constructing the comparison matrices. Also, this study assumes ranking 5 out of 10 in case of data unavailability in the indicator level (i.e. missing data means moderate, even impact of those indicators). An alternative of these assumptions is to determine a range of values based on surveying the experts in the area –practitioners and researchers.

The research area in sustainability can be divided into two major fields. One of them is related to indicator development and the other is related to sustainability assessment. These two fields are interconnected. The focus area of this study is sustainability assessment. Additionally, this study discussed various criteria to select indicators, various methods to develop and evaluate indicators as well as propose a classification system of indicators. These need to be further studied.

The indicators used in this research represent the output of several indicator development methods discussed in various studies and based on yearly technical reports from different agencies. For efficient processing these indicators need to be further investigated.

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APPENDIX A: AHP ANALYSIS FOR COMBINED SUSTAINABILITY

Appendix A: Comparison matrices Combined Sustainability

C=

Sustainable Transportation	Economic sustainability	Environmental sustainability	Social sustainability
Economic sustainability	1.00	1.00	1.00
Environmental sustainability	1.00	1.00	1.00
Social sustainability	1.00	1.00	1.00
Sum(S_{ci})	**3.00**	**3.00**	**3.00**

|N|=

Sustainable Transportation	Economic sustainability	Environmental sustainability	Social sustainability	**Avg(X_i)**
Economic sustainability	0.333	0.333	0.333	**0.333**
Environmental sustainability	0.333	0.333	0.333	**0.333**
Social sustainability	0.333	0.333	0.333	**0.333**

$|N|^2$=

Sustainable Transportation	Economic sustainability	Environmental sustainability	Social sustainability	**Avg(X_i)**	Dif.
Economic sustainability	0.333	0.333	0.333	**0.333**	0.000
Environmental sustainability	0.333	0.333	0.333	**0.333**	0.000
Social sustainability	0.333	0.333	0.333	**0.333**	0.000

n= 3

λ= $\lambda = \sum_{i=1}^{n} S_{ci} \times X_i$ 3

CI= $CI = \frac{\lambda - n}{n - 1}$ 0

CR= $CR = \frac{CI}{RI}$ 0.00 <0,10 ok

1 = Equal importance
3 = Moderately more important or slightly favorable
5 = Strongly more important or strongly favorable
7 = Demonstrated to be more important
9 = Demonstrated to have much more important

RI Table	
n=	*RI*
1	-
2	-
3	0.52
4	0.89
5	1.11

Appendix A: Combined Sustainability Index (Part 1)

First level	Second Level	Third Level		Bottom Level		Final Weight of each Indicator	Value Attributed to each Indicator	Final Result per Indicator
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	Truck throughput efficiency	0.750	0.042	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	Ensuring affordability	0.17	Per capita expenditures devoted to transport	1.000	0.028	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	Commuters using Public Transport	0.250	0.007	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	Change in congestion level	0.300	0.008	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	Increase accessibility	0.17	Average commute travel time (min)	1.000	0.028	[redacted]	[redacted]
[redacted]	[redacted]	Improve reliability	0.17	Ave. speed	0.500	0.014	[redacted]	[redacted]
[redacted]	[redacted]			Buffer index	0.500	0.014	[redacted]	[redacted]

Appendix A: Combined Sustainability Index Continued (Part 2)

Environmental sustainability	0.333	Climate protection and cleaner environment	0.50	Air, water, and soil pollution prevention	0.50	Water pollution	0.077	0.006	10	0.06
						Storm water treatment	0.077	0.006	5	0.03
						Release deicing chemicals and cleaning fluids	0.077	0.006	5	0.03
						Low emission vehicle purchased	0.231	0.019	5	0.10
						GHG emissions	0.462	0.038	5	0.19
						Others vehicle emissions	0.077	0.006	5	0.03
				Land use impact	0.50	Per capita land devoted to transport facility	0.333	0.028	10	0.28
						Impervious surfaces	0.333	0.028	5	0.14
						Preservation of wildlife habitat	0.333	0.028	5	0.14
		Environmental stability	0.50	Resource Conservation	1.00	Fuel efficiency	0.042	0.007	10	0.07
						Alternative fuel use	0.042	0.007	5	0.03
						Non-renewable recyclable resource (mineral) use	0.125	0.021	5	0.10
						Non-renewable non-recyclable resource (fossil fuel) use	0.375	0.063	5	0.31
						Per-capita gas use vs. urban density	0.375	0.063	5	0.31
						Recycling	0.042	0.007	5	0.03

Appendix A: Combined Sustainability Index Continued (Part 3)

Socially sustainable transportation	0.333	Transport planning	0.20	Universal design	0.33		1.000	0.022	5	0.11
				Citizen involvement	0.33		1.000	0.022	5	0.11
				Non-motorized transport planning	0.33	Degree to which non-motorized transport are considered in modeling	1.000	0.022	5	0.11
		Enhance safety	0.20	Better road condition	0.33	Potholes	0.500	0.011	10	0.11
						Road length with double or more lane	0.500	0.011	5	0.06
				Crash prevention and protection	0.33	Severe crashes	0.375	0.008	10	0.08
						Animal/wildlife collisions	0.062	0.001	5	0.01
						Accidental deaths	0.188	0.004	5	0.02
						Crash disabilities and fatalities	0.375	0.008	5	0.04
				Improve incident detection and response	0.33	Traffic monitoring coverage	1.000	0.022	5	0.11
		Increase cohesion and livability	0.20	Enhance public territory	0.33	Intensity of interactions among neighbors	1.000	0.022	5	0.11
				Improve local environmental quality	0.33	Satisfaction rating of transportation system	0.500	0.011	10	0.11
						Quality of padestrian and bicycle environment	0.167	0.004	5	0.02
						Time to next public transport stop	0.167	0.004	5	0.02
						Time to get to work place	0.167	0.004	5	0.02
				Improve accessibility to recreational places	0.33	Time devoted to recreational travel (min)	1.000	0.022	5	0.11
		Improve healty and fitness	0.20	Encourage non-motorized transport	0.50	Road length having footpath	0.500	0.017	10	0.17
						Population using non-motorized vehicle	0.500	0.017	5	0.08
				Reduce noise pollution	0.50	Population exposed to high levels of traffic noise	1.000	0.033	5	0.17
		Equity	0.20	Improve accessibility	0.25	Bus fleets/rail station compliant with disable act	1.000	0.017	5	0.08
				Horizontal and vertical equity	0.25	Degree to which prices reflect full costs	0.333	0.006	10	0.06
						Income inequality	0.667	0.011	5	0.06
				Affordability	0.25	HH expenditure on transportation	1.000	0.017	5	0.08
				Social disparities	0.25	Car ownership	1.000	0.017	5	0.08

***SI* = 5.95**

APPENDIX B: AHP ANALYSIS FOR ECONOMIC SUSTAINABILITY

APPENDIX B: Comparison Matrices for First Level Economic Sustainability

C=

Economic sustainability	Expand economic opportunity	Improve consumer's mobility
Expand economic opportunity	1.00	1.00
Improve consumer's mobility	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Economic sustainability	Expand economic opportunity	Improve consumer's mobility	**Avg(X_i)**
Expand economic opportunity	0.500	0.500	0.500
Improve consumer's mobility	0.500	0.500	0.500

1 = Equal importance

3 = Moderately more important or slightly favorable

5 = Strongly more important or strongly favorable

7 = Demonstrated to be more important

9 = Demonstrated to have much more important

Appendix B: Comparison matrices for Second Level Economic Sustainability

C=

Expand economic opportunity	Increase macro-economic contribution	Preserve value of transportation assets	Increase freight facility and service efficiency
Increase macro-economic contribution	1.00	1.00	1.00
Preserve value of transportation assets	1.00	1.00	1.00
Increase freight facility and service efficiency	1.00	1.00	1.00
Sum(S_{ci})	**3.00**	**3.00**	**3.00**

1 = Equal importance

3 = Moderately more important or slightly favorable

5 = Strongly more important or strongly favorable

7 = Demonstrated to be more important

9 = Demonstrated to have much more important

|N|=

Expand economic opportunity	Increase macro-economic contribution	Preserve value of transportation assets	Increase freight facility and service efficiency	Avg(X_i)
Increase macro-economic contribution	0.333	0.333	0.333	**0.333**
Preserve value of transportation assets	0.333	0.333	0.333	**0.333**
Increase freight facility and service efficiency	0.333	0.333	0.333	**0.333**

RI Table	
n=	*RI*
2	-
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35

$|N|^2$=

Expand economic opportunity	Increase macro-economic contribution	Preserve value of transportation assets	Increase freight facility and service efficiency	Avg(X_i)	Difference
Increase macro-economic contribution	0.333	0.333	0.333	**0.333**	0.000
Preserve value of transportation assets	0.333	0.333	0.333	**0.333**	0.000
Increase freight facility and service efficiency	0.333	0.333	0.333	**0.333**	0.000

n= 3 λ= 3.00 *CI*= 0.00 *CR*= 0.00 <0,10 ok

Appendix B: Comparison matrices for Second Level Economic Sustainability

C=

Improve consumer's mobility	Ensuring affordability	Increase public transport	Provide adequate services	Reduce congestion	Increase accessibility	Improve reliability
Ensuring affordability	1.00	1.00	1.00	1.00	1.00	1.00
Increase public transport	1.00	1.00	1.00	1.00	1.00	1.00
Provide adequate services	1.00	1.00	1.00	1.00	1.00	1.00
Reduce congestion	1.00	1.00	1.00	1.00	1.00	1.00
Increase accessibility	1.00	1.00	1.00	1.00	1.00	1.00
Improve reliability	1.00	1.00	1.00	1.00	1.00	1.00
Sum(S_{ci})	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**

|N|=

Improve consumer's mobility	Ensuring affordability	Increase public transport	Provide adequate services	Reduce congestion	Increase accessibility	Improve reliability	**Avg(X_i)**
Ensuring affordability	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**
Increase public transport	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**
Provide adequate services	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**
Reduce congestion	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**
Increase accessibility	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**
Improve reliability	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**

$|N|^2$=

Improve consumer's mobility	Ensuring affordability	Increase public transport	Provide adequate services	Reduce congestion	Increase accessibility	Improve reliability	**Avg(X_i)**	Dif
Ensuring affordability	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**	0.00
Increase public transport	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**	0.00
Provide adequate services	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**	0.00
Reduce congestion	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**	0.00
Increase accessibility	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**	0.00
Improve reliability	0.167	0.167	0.167	0.167	0.167	0.167	**0.167**	0.00

n= 6 λ= 6.00 *CI*= 0.00 *CR*= 0.00 <0,10 ok

Appendix B: Comparison matrices for Third Level Economic Sustainability

C=

Reduce congestion	Peak hour auto occupancy	Annual travel occurs in congestion	Change in congestion level	Per capita road length	Mode split	Per capita congestion costs
Peak hour auto occupancy	1.00	1.00	1.00	6.00	2.00	6.00
Annual travel occurs in congestion	1.00	1.00	1.00	6.00	2.00	6.00
Change in congestion level	1.00	1.00	1.00	6.00	2.00	6.00
Per capita road length	0.17	0.17	0.17	1.00	0.33	1.00
Mode split	0.50	0.50	0.50	3.00	1.00	3.00
Per capita congestion costs	0.17	0.17	0.17	1.00	0.33	1.00
Sum(S_{ci})	**3.83**	**3.83**	**3.83**	**23.00**	**7.67**	**23.00**

|N|=

Reduce congestion	Peak hour auto occupancy	Annual travel occurs in congestion	Change in congestion level	Per capita road length	Mode split	Per capita congestion costs	**Avg(X_i)**
Peak hour auto occupancy	0.261	0.261	0.261	0.261	0.261	0.261	**0.261**
Annual travel occurs in congestion	0.261	0.261	0.261	0.261	0.261	0.261	**0.261**
Change in congestion level	0.261	0.261	0.261	0.261	0.261	0.261	**0.261**
Per capita road length	0.043	0.043	0.043	0.043	0.043	0.043	**0.043**
Mode split	0.130	0.130	0.130	0.130	0.130	0.130	**0.130**
Per capita congestion costs	0.043	0.043	0.043	0.043	0.043	0.043	**0.043**

$|N|^2$=

Reduce congestion	Peak hour auto occupancy	Annual travel occurs in congestion	Change in congestion level	Per capita road length	Mode split	Per capita congestion costs	**Avg(X_i)**	Dif
Peak hour auto occupancy	0.261	0.261	0.261	0.261	0.261	0.261	**0.261**	0.00
Annual travel occurs in congestion	0.261	0.261	0.261	0.261	0.261	0.261	**0.261**	0.00
Change in congestion level	0.261	0.261	0.261	0.261	0.261	0.261	**0.261**	0.00
Per capita road length	0.043	0.043	0.043	0.043	0.043	0.043	**0.043**	0.00
Mode split	0.130	0.130	0.130	0.130	0.130	0.130	**0.130**	0.00
Per capita congestion costs	0.043	0.043	0.043	0.043	0.043	0.043	**0.043**	0.00
n= 6		λ= 6.00		CI= 0.00		CR= 0.00	<0,10	ok

Appendix B: Comparison matrices for Third Level Economic Sustainability

N=

Increase Public Transportation	Commuters using Public Transport	Portion of Public Transport	Portion of rail commuters in Public Transport	Quality of Public Transport
Commuters using Public Transport	1.00	1.00	5.00	5.00
Portion of Public Transport	1.00	1.00	5.00	5.00
Portion of rail commuters in Public Transport	0.20	0.20	1.00	1.00
Quality of Public Transport	0.20	0.20	1.00	1.00
Sum(S_{ci})	**2.40**	**2.40**	**12.00**	**12.00**

|N|=

Increase Public Transportation	Commuters using Public Transport	Portion of Public Transport	Portion of rail commuters in Public Transport	Quality of Public Transport	Avg(X_i)
Commuters using Public Transport	0.42	0.42	0.42	0.42	**0.42**
Portion of Public Transport	0.42	0.42	0.42	0.42	**0.42**
Portion of rail commuters in Public Transport	0.08	0.08	0.08	0.08	**0.08**
Quality of Public Transport	0.08	0.08	0.08	0.08	**0.08**

$|N|^2$=

Increase Public Transportation	Commuters using Public Transport	Portion of Public Transport	Portion of rail commuters in Public Transport	Quality of Public Transport	Avg(X_i)	Dif
Commuters using Public Transport	0.42	0.42	0.42	0.42	**0.42**	0.00
Portion of Public Transport	0.42	0.42	0.42	0.42	**0.42**	0.00
Portion of rail commuters in Public Transport	0.08	0.08	0.08	0.08	**0.08**	0.00
Quality of Public Transport	0.08	0.08	0.08	0.08	**0.08**	0.00

n= 4 λ= 4.00 CI= 0.00 CR= 0.00

Appendix B: Comparison matrices for Third Level Economic Sustainability

C=

Provide adequate services	Percapita shprt journeys per year	Ave. H-W trip distance
Percapita shprt journeys per year	1.00	1.00
Ave. H-W trip distance	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Provide adequate services	Percapita shprt journeys per year	Ave. H-W trip distance	**Avg(X_i)**
Percapita shprt journeys per year	0.500	0.500	0.500
Ave. H-W trip distance	0.500	0.500	0.500

C=

Improve reliability	Ave. speed	Buffer index
Ave. speed	1.00	1.00
Buffer index	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Improve reliability	Ave. speed	Buffer index	**Avg(X_i)**
Ave. speed	0.500	0.500	0.500
Buffer index	0.500	0.500	0.500

1 = Equal importance
3 = Moderately more important or slightly favorable
5 = Strongly more important or strongly favorable
7 = Demonstrated to be more important
9 = Demonstrated to have much more important

Appendix B: Comparison matrices for Third Level Economic Sustainability

C=

Increase macro-economic contribution	Contribution towards GDP	Impact on employment	Degree to which planning reflect least-cost and investment practices
Contribution towards GDP	1.00	2.00	1.00
Impact on employment	0.50	1.00	0.50
Degree to which planning reflect least-cost and investment practices	1.00	2.00	1.00
Sum(S_{ci})	**2.50**	**5.00**	**2.50**

|N|=

Increase macro-economic contribution	Contribution towards GDP	Impact on employment	Degree to which planning reflect least-cost and investment practices	**Avg(X_i)**
Contribution towards GDP	0.400	0.400	0.400	**0.400**
Impact on employment	0.200	0.200	0.200	**0.200**
Degree to which planning reflect least-cost and investment practices	0.400	0.400	0.400	**0.400**

$|N|^2$=

Increase macro-economic contribution	Contribution towards GDP	Impact on employment	Degree to which planning reflect least-cost and investment practices	**Avg(X_i)**	Dif
Contribution towards GDP	0.400	0.400	0.400	**0.400**	0.00
Impact on employment	0.200	0.200	0.200	**0.200**	0.00
Degree to which planning reflect least-cost and investment practices	0.400	0.400	0.400	**0.400**	0.00

λ= 3.0 CI= 0.0 CR= 0.0 <0,10

Appendix B: Comparison matrices for Third Level Economic Sustainability

C=

Increase freight facility and service efficiency	Load factors for freight transport	Truck throughput efficiency
Load factors for freight transport	1.00	0.20
Truck throughput efficiency	5.00	1.00
Sum(S_{ci})	**6.00**	**1.20**

|N|=

Increase freight facility and service efficiency	Load factors for freight transport	Truck throughput efficiency	**Avg(X_i)**
Load factors for freight transport	0.167	0.167	0.167
Truck throughput efficiency	0.833	0.833	0.833

C=

Preserve value of transportation assets	Ave. pvt. condition score	Proportion of non-single occupant travel
Ave. pvt. condition score	1.00	1.00
Proportion of non-single occupant travel	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Preserve value of transportation assets	Ave. pvt. condition score	Proportion of non-single occupant travel	**Avg(X_i)**
Ave. pvt. condition score	0.500	0.500	0.500
Proportion of non-single occupant travel	0.500	0.500	0.500

Appendix B: Economic Sustainability Index

First level	Second Level		Third Level		Bottom Level		Final Weight of each Indicator	Value Attributed to each Indicator	Final Result per Indicator
Economic sustainability	Expand economic opportunity	0.500	Increase macro-economic contribution	0.333	Contribution towards GDP	0.400	0.067	10	0.667
					Impact on employment	0.200	0.033	5	0.167
					Degree to which planning reflect least-cost and investment practices	0.400	0.067	5	0.333
			Preserve value of transportation assets	0.333	Load factors for freight transport	0.167	0.028	10	0.278
					Truck throughput efficiency	0.833	0.139	5	0.694
			Increase freight facility and service efficiency	0.333	Ave. pvt. condition score	0.500	0.083	10	0.833
					Proportion of non-single occupant travel	0.500	0.083	5	0.417
	Improve consumer's mobility	0.500	Ensuring affordability	0.167	Per capita expenditures devoted to transport	1.000	0.083	5	0.417
			Increase public transport	0.167	Commuters using Public Transport	0.417	0.035	10	0.347
					Portion of Public Transport	0.417	0.035	5	0.174
					Portion of rail commuters in Public Transport	0.083	0.007	5	0.035
					Quality of Public Transport	0.083	0.007	5	0.035
			Provide adequate services	0.167	Percapita shprt journeys per year	0.500	0.042	10	0.417
					Ave. H-W trip distance	0.500	0.042	5	0.208
			Reduce congestion	0.167	Peak hour auto occupancy	0.261	0.022	10	0.217
					Annual travel occurs in congestion	0.261	0.022	5	0.109
					Change in congestion level	0.261	0.022	5	0.109
					Per capita road length	0.043	0.004	5	0.018
					Mode split	0.130	0.011	5	0.054
					Per capita congestion costs	0.043	0.004	5	0.018
			Increase accessibility	0.167	Average commute travel time	1.000	0.083	5	0.417
			Improve reliability	0.167	Ave. speed	0.500	0.042	10	0.417
					Buffer index	0.500	0.042	5	0.208
						Sum =	1	**Score =**	**6.59**

APPENDIX C: AHP ANALYSIS FOR ENVIRONMENTAL SUSTAINABILITY

Appendix C: Comparison matrices for First Level Environmental Sustainability

C=

Environmental sustainability	Climate protection and cleaner environment	Environmental stability
Climate protection and cleaner environment	1.00	1.00
Environmental stability	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Environmental sustainability	Climate protection and cleaner environment	Environmental stability	**Avg(X_i)**
Climate protection and cleaner environment	0.500	0.500	0.500
Environmental stability	0.500	0.500	0.500

Appendix C: Comparison matrices for Second Level Environmental Sustainability

C=

Climate protection and cleaner environment	Air, water, and soil pollution prevention	Land use impact
Air, water, and soil pollution prevention	1.00	1.00
Land use impact	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Climate protection and cleaner environment	Air, water, and soil pollution prevention	Land use impact	**Avg(X_i)**
Air, water, and soil pollution prevention	0.500	0.500	0.500
Land use impact	0.500	0.500	0.500

Appendix C: Comparison matrices for Third Level Environmental Sustainability

C=

Air, water, and soil pollution prevention	Water pollution	Storm water treatment	Release deicing chemicals and cleaning fluids	Low emission vehicle purchased	GHG emissions	Others vehicle emissions
Water pollution	1.00	1.00	1.00	0.33	0.17	1.00
Storm water treatment	1.00	1.00	1.00	0.33	0.17	1.00
Release deicing chemicals and cleaning fluids	1.00	1.00	1.00	0.33	0.17	1.00
Low emission vehicle purchased	3.00	3.00	3.00	1.00	0.50	3.00
GHG emissions	6.00	6.00	6.00	2.00	1.00	6.00
Others vehicle emissions	1.00	1.00	1.00	0.33	0.17	1.00
Sum(S_{ci})	**13.00**	**13.00**	**13.00**	**4.33**	**2.17**	**13.00**

|N|=

Air, water, and soil pollution prevention	Water pollution	Storm water treatment	Release deicing chemicals and cleaning fluids	Low emission vehicle purchased	GHG emissions	Others vehicle emissions	**Avg(X_i)**
Water pollution	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**
Storm water treatment	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**
Release deicing chemicals and cleaning fluids	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**
Low emission vehicle purchased	0.231	0.231	0.231	0.231	0.231	0.231	**0.231**
GHG emissions	0.462	0.462	0.462	0.462	0.462	0.462	**0.462**
Others vehicle emissions	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**

$|N|^2$=

Air, water, and soil pollution prevention	Water pollution	Storm water treatment	Release deicing chemicals and cleaning fluids	Low emission vehicle purchased	GHG emissions	Others vehicle emissions	**Avg(X_i)**	Dif
Water pollution	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**	0.000
Storm water treatment	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**	0.000
Release deicing chemicals and cleaning fluids	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**	0.000
Low emission vehicle purchased	0.231	0.231	0.231	0.231	0.231	0.231	**0.231**	0.000
GHG emissions	0.462	0.462	0.462	0.462	0.462	0.462	**0.462**	0.000
Others vehicle emissions	0.077	0.077	0.077	0.077	0.077	0.077	**0.077**	0.000

n= 6 λ= 6.00 *CI*= 0.00 *CR*= 0.00 <0,10 ok

Appendix C: Comparison matrices for Third Level Environmental Sustainability

C=

Land use impact	Per capita land devoted to transport facility	Impervious surfaces	Preservation of wildlife habitat
Per capita land devoted to transport facility	1.00	1.00	1.00
Impervious surfaces	1.000	1.00	1.00
Preservation of wildlife habitat	1.00	1.000	1.00
Sum(S_{ci})	**3.00**	**3.00**	**3.00**

RI Table	
n=	*RI*
1	-
2	-
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40

|N|=

Land use impact	Per capita land devoted to transport facility	Impervious surfaces	Preservation of wildlife habitat	**Avg(X_i)**
Per capita land devoted to transport facility	0.333	0.333	0.333	**0.333**
Impervious surfaces	0.333	0.333	0.333	**0.333**
Preservation of wildlife habitat	0.333	0.333	0.333	**0.333**

$|N|^2$=

Land use impact	Per capita land devoted to transport facility	Impervious surfaces	Preservation of wildlife habitat	**Avg(X_i)**	Dif
Per capita land devoted to transport facility	0.333	0.333	0.333	**0.333**	0.000
Impervious surfaces	0.333	0.333	0.333	**0.333**	0.000
Preservation of wildlife habitat	0.333	0.333	0.333	**0.333**	0.000

n = 3 λ= 3.00 *CI*= 0.000 *CR*= 0.00 <0,10 ok

Appendix C: Comparison matrices for Third Level Environmental Sustainability

C=

Resource conservation	Fuel efficiency	Alternative fuel use	Mineral use	Fossil fuel use	Per-capita gas use vs. urban density	Recycling
Fuel efficiency	1.00	1.00	0.33	0.11	0.11	1.00
Alternative fuel use	1.00	1.00	0.33	0.11	0.11	1.00
Mineral use	3.00	3.00	1.00	0.33	0.33	3.00
Fossil fuel use	9.00	9.00	3.00	1.00	1.00	9.00
Per-capita gas use vs. urban density	9.00	9.00	3.00	1.00	1.00	9.00
Recycling	1.00	1.00	0.33	0.11	0.11	1.00
Sum(S_{ci})	**24.00**	**24.00**	**8.00**	**2.67**	**2.67**	**24.00**

RI Table	
n=	*RI*
1	-
2	-
3	0.52
4	0.89
5	1.11
6	1.25

|N|=

Resource conservation	Fuel efficiency	Alternative fuel use	Mineral use	Fossil fuel use	Per-capita gas use vs. urban density	Recycling	**Avg(X_i)**
Fuel efficiency	0.042	0.042	0.042	0.042	0.042	0.042	**0.042**
Alternative fuel use	0.042	0.042	0.042	0.042	0.042	0.042	**0.042**
Mineral use	0.125	0.125	0.125	0.125	0.125	0.125	**0.125**
Fossil fuel use	0.375	0.375	0.375	0.375	0.375	0.375	**0.375**
Per-capita gas use vs. urban density	0.375	0.375	0.375	0.375	0.375	0.375	**0.375**
Recycling	0.042	0.042	0.042	0.042	0.042	0.042	**0.042**

$|N|^2$=

Resource conservation	Fuel efficiency	Alternative fuel use	Mineral use	Fossil fuel use	Per-capita gas use vs. urban density	Recycling	**Avg(X_i)**	Dif
Fuel efficiency	0.042	0.042	0.042	0.042	0.042	0.042	**0.042**	0.00
Alternative fuel use	0.042	0.042	0.042	0.042	0.042	0.042	**0.042**	0.00
Mineral use	0.125	0.125	0.125	0.125	0.125	0.125	**0.125**	0.00
Fossil fuel use	0.375	0.375	0.375	0.375	0.375	0.375	**0.375**	0.00
Per-capita gas use vs. urban density	0.375	0.375	0.375	0.375	0.375	0.375	**0.375**	0.00
Recycling	0.042	0.042	0.042	0.042	0.042	0.042	**0.042**	0.00

n= 6 λ= 6.00 *CI*= 0.00 *CR*= 0.00 <0,10 ok

Appendix C: Environmental Sustainability Index

First level	Second Level		Third Level		Bottom Level		Final Weight of each Indicator	Value Attributed to each Indicator	Final Result per Indicator
Environmental sustainability	Climate protection and cleaner environment	0.5	Air, water, and soil pollution prevention	0.5	Water pollution	0.077	0.019	10	0.192
					Storm water treatment	0.077	0.019	5	0.096
					Release deicing chemicals and cleaning fluids	0.077	0.019	5	0.096
					Low emission vehicle purchased	0.231	0.058	5	0.288
					GHG emissions	0.462	0.115	5	0.577
					Others vehicle emissions	0.077	0.019	5	0.096
			Land use impact	0.5	Per capita land devoted to transport facility	0.333	0.083	10	0.833
					Impervious surfaces	0.333	0.083	5	0.417
					Preservation of wildlife habitat	0.333	0.083	5	0.417
	Environmental stability	0.5	Resource Conservation	1	Fuel efficiency	0.042	0.021	10	0.208
					Alternative fuel use	0.042	0.021	5	0.104
					Mineral use	0.125	0.063	5	0.313
					Fossil fuel use	0.375	0.188	5	0.938
					urban density	0.375	0.188	5	0.938
					Recycling	0.042	0.021	5	0.104
						Sum =	1	**Score =**	**5.62**

APPENDIX D: AHP ANALYSIS FOR SOCIAL SUSTAINABILITY

Appendix D: Comparison matrices for First Level Social Sustainability

C=

Socially sustainable transportation	Transport planning	Enhance safety	Increase cohesion and livability	Improve healty and fitness	Equity
Transport planning	1.00	1.00	1.00	1.00	1.00
Enhance safety	1.00	1.00	1.00	1.00	1.00
Increase cohesion and livability	1.00	1.00	1.00	1.00	1.00
Improve healty and fitness	1.00	1.00	1.00	1.00	1.00
Equity	1.00	1.00	1.00	1.00	1.00
Sum(S_{ci})	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**

RI Table	
n=	*RI*
1	-
2	-
3	0.52
4	0.89
5	1.11
6	1.25

|N|=

Socially sustainable transportation	Transport planning	Enhance safety	Increase cohesion and livability	Improve healty and fitness	Equity	**Avg(X_i)**
Transport planning	0.200	0.200	0.200	0.200	0.200	**0.200**
Enhance safety	0.200	0.200	0.200	0.200	0.200	**0.200**
Increase cohesion and livability	0.200	0.200	0.200	0.200	0.200	**0.200**
Improve healty and fitness	0.200	0.200	0.200	0.200	0.200	**0.200**
Equity	0.200	0.200	0.200	0.200	0.200	**0.200**

$|N|^2=$

Socially sustainable transportation	Transport planning	Enhance safety	Increase cohesion and livability	Improve healty and fitness	Equity	**Avg(X_i)**	Dif
Transport planning	0.200	0.200	0.200	0.200	0.200	**0.200**	0.00
Enhance safety	0.200	0.200	0.200	0.200	0.200	**0.200**	0.00
Increase cohesion and livability	0.200	0.200	0.200	0.200	0.200	**0.200**	0.00
Improve healty and fitness	0.200	0.200	0.200	0.200	0.200	**0.200**	0.00
Equity	0.200	0.200	0.200	0.200	0.200	**0.200**	0.00

n= 5 λ= 5 *CI*= 0.00 *CR*= 0.00 <0,10

Appendix D: Comparison matrices for Second Level Social Sustainability

C=

Transport planning	Universal design	Citizen involvement	Non-motorized
Universal design	1.00	1.00	1.00
Citizen involvement	1.00	1.00	1.00
Non-motorized transport planning	1.00	1.00	1.00
Sum(S_{ci})	**3.00**	**3.00**	**3.00**

|N|=

Transport planning	Universal design	Citizen involvement	Non-motorized	**Avg(X_i)**
Universal design	0.333	0.333	0.333	**0.333**
Citizen involvement	0.333	0.333	0.333	**0.333**
Non-motorized transport planning	0.333	0.333	0.333	**0.333**

$|N|^2$=

Transport planning	Universal design	Citizen involvement	Non-motorized	**Avg(X_i)**	Dif.
Universal design	0.333	0.333	0.333	**0.333**	0.00
Citizen involvement	0.333	0.333	0.333	**0.333**	0.00
Non-motorized transport planning	0.333	0.333	0.333	**0.333**	0.00

n= 3 λ= 3 *CI*= 0.0

CR= 0.00 <0,10

Appendix D: Comparison matrices for Second Level Social Sustainability

C=

Enhance safety	Better road condition	Crash prevention and protection	Improve incident detection and response
Better road condition	1.00	1.00	1.00
Crash prevention and protection	1.00	1.00	1.00
Improve incident detection and response	1.00	1.00	1.00
Sum(S_{ci})	**3.00**	**3.00**	**3.00**

|N|=

Enhance safety	Better road condition	Crash prevention and protection	Improve incident detection and response	**Avg(X_i)**
Better road condition	0.333	0.333	0.333	**0.333**
Crash prevention and protection	0.333	0.333	0.333	**0.333**
Improve incident detection and response	0.333	0.333	0.333	**0.333**

$|N|^2$=

Enhance safety	Better road condition	Crash prevention and protection	Improve incident detection and response	**Avg(X_i)**	Dif.
Better road condition	0.333	0.333	0.333	**0.333**	0.00
Crash prevention and protection	0.333	0.333	0.333	**0.333**	0.00
Improve incident detection and response	0.333	0.333	0.333	**0.333**	0.00

n= 3 λ= 3.000 CI= 0.000

CR= 0.00 <0,10

Appendix D: Comparison matrices for Second Level Social Sustainability

C=

Increase cohesion and livability	Enhance public territory	Improve local environmental quality	Improve accessibility to recreational places
Enhance public territory	1.00	1.00	1.00
Improve local environmental quality	1.00	1.00	1.00
Improve accessibility to recreational places	1.00	1.00	1.00
Sum(S_{ci})	**3.00**	**3.00**	**3.00**

|N|=

Increase cohesion and livability	Enhance public territory	Improve local environmental quality	Improve accessibility to recreational places	**Avg(X_i)**
Enhance public territory	0.333	0.333	0.333	**0.333**
Improve local environmental quality	0.333	0.333	0.333	**0.333**
Improve accessibility to recreational places	0.333	0.333	0.333	**0.333**

$|N|^2$=

Increase cohesion and livability	Enhance public territory	Improve local environmental quality	Improve accessibility to recreational places	**Avg(X_i)**	Dif.
Enhance public territory	0.333	0.333	0.333	**0.333**	0.00
Improve local environmental quality	0.333	0.333	0.333	**0.333**	0.00
Improve accessibility to recreational places	0.333	0.333	0.333	**0.333**	0.00

n= 3 λ= 3 *CI*= 0

CR= 0.00 <0,10

Appendix D: Comparison matrices for Second Level Social Sustainability

C=

Improve healty and fitness	Encourage non-motorized transport	Reduce noise pollution
Encourage non-motorized transport	1.00	1.00
Reduce noise pollution	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Improve healty and fitness	Encourage non-motorized transport	Reduce noise pollution	**Avg(X_i)**
Encourage non-motorized transport	0.500	0.500	0.500
Reduce noise pollution	0.500	0.500	0.500

C=

Equity	Improve accessibility	Horizontal and vertical equity	Affordability	Social disparities
Improve accessibility	1.00	1.00	1.00	1.00
Horizontal and vertical equity	1.00	1.00	1.00	1.00
Affordability	1.00	1.00	1.00	1.00
Social disparities	1.00	1.00	1.00	1.00
Sum(S_{ci})	**4.00**	**4.00**	**4.00**	**4.00**

|N|=

Equity	Improve accessibility	Horizontal and vertical equity	Affordability	Social disparities	**Avg(X_i)**
Improve accessibility	0.25	0.25	0.25	0.25	**0.25**
Horizontal and vertical equity	0.25	0.25	0.25	0.25	**0.25**
Affordability	0.25	0.25	0.25	0.25	**0.25**
Social disparities	0.25	0.25	0.25	0.25	**0.25**

$|N|^2$=

Equity	Improve accessibility	Horizontal and vertical equity	Affordability	Social disparities	**Avg(X_i)**	Dif
Improve accessibility	0.25	0.25	0.25	0.25	**0.25**	0.00
Horizontal and vertical equity	0.25	0.25	0.25	0.25	**0.25**	0.00
Affordability	0.25	0.25	0.25	0.25	**0.25**	0.00
Social disparities	0.25	0.25	0.25	0.25	**0.25**	0.00

n= 4 λ= 4.00 CR= 0.00 <0,10 ok CI= 0.00

Appendix D: Comparison matrices for Third Level Social Sustainability

C=

Better road condition	Potholes	Road length with double or more lane
Potholes	1.00	1.00
Road length with double or more lane	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Better road condition	Potholes	Road length with double or more lane	**Avg(X_i)**
Potholes	0.500	0.500	0.500
Road length with double or more lane	0.500	0.500	0.500

C=

Crash prevention and protection	Severe crashes	Animal/wildlife collisions	Accidental deaths	Crash disabilities and fatalities
Severe crashes	1.00	6.00	2.00	1.00
Animal/wildlife collisions	0.17	1.00	0.33	0.17
Accidental deaths	0.50	3.00	1.00	0.50
Crash disabilities and fatalities	1.00	6.00	2.00	1.00
Sum(S_{ci})	**2.67**	**16.00**	**5.33**	**2.67**

|N|=

Crash prevention and protection	Severe crashes	Animal/wildlife collisions	Accidental deaths	Crash disabilities and fatalities	**Avg(X_i)**
Severe crashes	0.38	0.38	0.38	0.38	**0.38**
Animal/wildlife collisions	0.06	0.06	0.06	0.06	**0.06**
Accidental deaths	0.19	0.19	0.19	0.19	**0.19**
Crash disabilities and fatalities	0.38	0.38	0.38	0.38	**0.38**

$|N|^2$=

Crash prevention and protection	Severe crashes	Animal/wildlife collisions	Accidental deaths	Crash disabilities and fatalities	**Avg(X_i)**	Dif
Severe crashes	0.38	0.38	0.38	0.38	**0.38**	0.00
Animal/wildlife collisions	0.06	0.06	0.06	0.06	**0.06**	0.00
Accidental deaths	0.19	0.19	0.19	0.19	**0.19**	0.00
Crash disabilities and fatalities	0.38	0.38	0.38	0.38	**0.38**	0.00

n= 4 λ= 4 CI= 0 CR= 0 <0,1

Appendix D: Comparison matrices for Third Level Social Sustainability

N=

Improve local environmental quality	Satisfaction rating of transportation system	Quality of padestrian and bicycle environment	Time to next public transport stop	Time to get to work place
Satisfaction rating of transportation system	1.00	5.00	5.00	5.00
Quality of padestrian and bicycle environment	0.20	1.00	1.00	1.00
Time to next public transport stop	0.20	1.00	1.00	1.00
Time to get to work place	0.20	1.00	1.00	1.00
Sum(S_{ci})	**1.60**	**8.00**	**8.00**	**8.00**

|N|=

Improve local environmental quality	Satisfaction rating of transportation system	Quality of padestrian and bicycle environment	Time to next public transport stop	Time to get to work place	**Avg(X_i)**
Satisfaction rating of transportation system	0.63	0.63	0.63	0.63	**0.63**
Quality of padestrian and bicycle environment	0.13	0.13	0.13	0.13	**0.13**
Time to next public transport stop	0.13	0.13	0.13	0.13	**0.13**
Time to get to work place	0.13	0.13	0.13	0.13	**0.13**

$|N|^2$=

Improve local environmental quality	Satisfaction rating of transportation system	Quality of padestrian and bicycle environment	Time to next public transport stop	Time to get to work place	**Avg(X_i)**	Dif
Satisfaction rating of transportation system	0.63	0.63	0.63	0.63	**0.63**	0.00
Quality of padestrian and bicycle environment	0.13	0.13	0.13	0.13	**0.13**	0.00
Time to next public transport stop	0.13	0.13	0.13	0.13	**0.13**	0.00
Time to get to work place	0.13	0.13	0.13	0.13	**0.13**	0.00

n= 4 λ= 4.00 CI= 0.00 CR= 0.00 <0,1

Appendix D: Comparison matrices for Third Level Social Sustainability

C=

Encourage non-motorized transport	Road length having footpath	Population using non-motorized vehicle
Road length having footpath	1.00	1.00
Population using non-motorized vehicle	1.00	1.00
Sum(S_{ci})	**2.00**	**2.00**

|N|=

Encourage non-motorized transport	Road length having footpath	Population using non-motorized vehicle	**Avg(X_i)**
Road length having footpath	0.500	0.500	0.500
Population using non-motorized vehicle	0.500	0.500	0.500

C=

Horizontal and vertical equity	Degree to which prices reflect full costs	Income inequality
Degree to which prices reflect full costs	1.00	0.33
Income inequality	3.00	1.00
Sum(S_{ci})	**4.00**	**1.33**

|N|=

Horizontal and vertical equity	Degree to which prices reflect full costs	Income inequality	**Avg(X_i)**
Degree to which prices reflect full costs	0.250	0.250	0.250
Income inequality	0.750	0.750	0.750

Appendix D: Social Sustainability Index

First level	Second Level		Third Level		Bottom Level		Final Weight of each Indicator	Value Attributed to each Indicator	Final Result per Indicator
Socially sustainable transportation	Transport planning	0.2	Universal design	0.33		1.00	0.067	5	0.333
			Citizen involvement	0.33		1.00	0.067	5	0.333
			Non-motorized transport planning	0.33	Degree to which non-motorized transport are considered in modeling	1.00	0.067	5	0.333
	Enhance safety	0.2	Better road condition	0.33	Potholes	0.50	0.033	10	0.333
					Road length with double or more lane	0.50	0.033	5	0.167
			Crash prevention and protection	0.33	Severe crashes	0.32	0.021	10	0.214
					Animal/wildlife collisions	0.04	0.002	5	0.012
					Accidental deaths	0.32	0.021	5	0.107
					Crash disabilities and fatalities	0.32	0.021	5	0.107
			Improve incident detection and response	0.33	Traffic monitoring coverage	1.00	0.067	5	0.333
	Increase cohesion and livability	0.2	Enhance public territory	0.33	Intensity of interactions among neighbors	1.00	0.067	5	0.333
			Improve local environmental quality	0.33	Satisfaction rating of transportation system	0.63	0.042	10	0.417
					Quality of pedestrian and bicycle environment	0.13	0.008	5	0.042
					Time to next public transport stop	0.13	0.008	5	0.042
					Time to get to work place	0.13	0.008	5	0.042
			Improve accessibility to recreational places	0.33	Time devoted to recreational travel	1.00	0.067	5	0.333
	Improve healty and fitness	0.2	Encourage non-motorized transport	0.50	Road length having footpath	0.50	0.050	10	0.500
					Population using non-motorized vehicle	0.50	0.050	5	0.250
			Reduce noise pollution	0.50	Population exposed to high levels of traffic noise	1.00	0.100	5	0.500
	Equity	0.2	Improve accessibility	0.25	Bus fleets/rail station compliant with disable act	1.00	0.050	5	0.250
			Horizontal and vertical equity	0.25	Degree to which prices reflect full costs	0.25	0.013	10	0.125
					Income inequality	0.75	0.038	5	0.188
			Affordability	0.25	HH expenditure on transportation	1.00	0.050	5	0.250
			Social disparities	0.25	Car ownership	1.00	0.050	5	0.250
							SUM = 1	Score=	5.79

APPENDIX E: SPSS OUTPUT FOR INDICATORS

Appendix E: Statistical Package for the Social Sciences (SPSS) output for Economic indicator

Economical Sustainability

Indicator	CANSIM SOURCE	No of Observations	F_0	Adj. R^2	β_0	Sig. (β_0)	β_1	Sig. (β_1)	Scoring out of 10
Peak hour auto occupancy to from CBD	Table 405-0074	10	3.83	0.41	1.87	0.26	-2.10	0.11	6
Change in level of road congestion over time	Table 405-0029	38	7.70	0.52	-0.68	0.02	0.06	0.39	6
Annual travel occurs in congested conditions	Table 405-0028	38	0.37	0.54	-1.87	0.00	0.38	0.00	6
Contribution towards GDP	Table 402-0001	12	3.74	0.67	0.93	0.15	-0.66	0.01	6
Per capita short journeys	Table 405-0051	13	0.01	0.68	-0.33	0.52	0.66	0.05	7
Average home-work trip distancetime	Table 405-0049	13	2.65	0.69	-1.79	0.00	1.15	0.00	7
Impact on employment	Table 408-0007	8	111.65	0.94	-1.79	0.00	0.40	0.00	3
Throughput efficiency	Table 405-0055	10	538.79	0.99	-1.56	0.00	0.21	0.00	5
Degree to which planning reflect least-cost and investment practices	Table 408-0004	124	1067.95	0.99	-1.46	0.00	0.02	0.00	6
Commuters using public transport	Table 405-0092	4	6.28	1.00	7.36	0.00	-8.68	0.00	5
Mode split	Table 405-0093	4	6.23	1.00	7.36	0.00	-8.68	0.00	3
Per capita expenditures devoted to transport	Table 079-0004	4	80.52	1.00	-1.27	0.00	0.13	0.00	7
Portion of public transport in total	Table 079-0004	4	8.18	1.00	5.32	0.00	-5.31	0.00	5

Appendix E: Statistical Package for the Social Sciences (SPSS) output for Social indicator

Social sustainability

Indicator	CANSIM SOURCE	No of Observations	F_0	Adj. R^2	β_0	Sig. (β_0)	β_1	Sig. (β_1)	β_2	Sig. (β_2)	Scoring out of 10
Crash disabilities and fatalities	Table 409-0003	23	0.48	0.06	-0.61	0.37	0.19	0.16	-0.01	0.11	9
Severe crashes	Table 409-0003	23	1.42	0.07	-0.32	0.63	0.15	0.26	-0.01	0.15	9
Accidental deaths	Table 409-0003	23	4.21	0.29	-0.36	0.54	0.20	0.09	-0.01	0.03	9
Bus fleets compliant with disable act	Table 405-0004	23	68.54	0.53	-2.47	0.00	0.74	0.00	-0.06	0.01	7
Time devoted to recreational travel	Table 405-0025	14	0.83	0.58	0.53	0.03	-0.30	0.03	0.05	0.02	5
Satisfaction rating of transportation system	Table 409-0001	23	8.01	0.64	3.05	0.00	-0.71	0.00	0.04	0.05	5
Income inequality	Table 079-0003	279	5.86	0.83	-1.09	0.00	0.00	0.05	0.00	0.00	3
Car ownership	Table 405-0014	5	11.98	0.98	-0.39	0.52	-0.62	0.45	0.34	0.33	5

Appendix E: Statistical Package for the Social Sciences (SPSS) output for Environmental indicator

Environmental Sustainability

Indicator	CANSIM SOURCE	No of Observations	F_0	Adj. R^2	β_0	Sig. (β_0)	β_1	Sig. (β_1)	Scoring out of 10
Low emission vehicles purchased	Table 405-0004	12	44.33	0.83	-0.61	0.39	1.18	0.03	3
Alternative fuel use	Table 153-0014	21	19.82	0.92	3.16	0.00	-0.67	0.00	1
Per capita gas use	Table 131-0001	277	3212.92	0.98	-2.03	0.00	0.03	0.00	9
Fossil fuel use	Table 126-0001	278	3212.92	0.98	-1.83	0.00	0.02	0.00	9
Mineral use	Table 405-0003	228	326.20	0.98	-1.50	0.00	0.02	0.00	3
GHG emissions	Table 153-0033	19	661.30	0.98	1.49	0.00	-0.02	0.80	6