AN IMPROVED METHODOLOGY FOR MULTI-CRITERIA ASSESSMENT OF HIGHWAY SUSTAINABILITY

A Thesis

by

TARA LAKSHMI RAMANI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2008

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Luca Quadrifoglio
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ABSTRACT

An Improved Methodology for Multi-Criteria Assessment of Highway
Sustainability. (August 2008)
Tara Lakshmi Ramani, B.En., Anna University
Chair of Advisory Committee: Dr. Luca Quadrifoglio

The concept of sustainability has been widely discussed in relation to human activity and scientific development in recent times. There is an increased awareness of the current and future ramifications of people's everyday activities on the environment, and sustainable development aims to mitigate these impacts, as well as promote social equity and economic efficiency. A majority of research concerned with transportation sustainability addresses it at the policy-planning level, though there have been recent attempts at quantitatively evaluating it. These evaluations are mostly based on multi-criteria decision making processes using performance measures. However, the methods and the performance measures developed are often not geared toward being practically implemented within a transportation agency's regular planning activities.

This research effort seeks to improve upon existing sustainability evaluation processes for highways by proposing a methodology that addresses sustainability within the regular transportation planning paradigm, rather than as a separate concern. A more scientific approach to the scaling of various performance measures, as well as the evaluation of current and future planning scenarios on a common basis provides for an improved multi-criteria evaluation method. A case study was conducted using the proposed methodology for a section of US Highway 281 in San Antonio, Texas. The evaluation model developed in this study provides the basis for further research into applying decision-making processes to improve transportation sustainability by addressing some of the inherent drawbacks of existing research on sustainability evaluation.

ACKNOWLEDGEMENTS

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NOMENCLATURE

ADT- Average Daily Traffic

CO- Carbon Monoxide

CO_2 – Carbon Dioxide

DOT – Department of Transportation

EPA- Environmental Protection Agency

GIS- Geographic Information Systems

GPL- General Purpose Lane

HOV- High Occupancy Vehicle

ITS- Intelligent Transportation Systems

MAUT- Multi-Attribute Utility Theory

MCDM- Multi-Criteria Decision Making

MEV- Million Entering Vehicles

MPO- Metropolitan Planning Organization

MVMT- Million Vehicle Miles of Travel

NAAQS- National Ambient Air Quality Standards

NO_x – Oxides of Nitrogen

PMIS- Pavement Management Information System

PMT- Person-Miles of Travel

RHiNo- Road-Highway Inventory Network

ROW- Right-of-Way

SOV- Single Occupant Vehicle

TMC- Traffic Monitoring Center

TTI – Texas Transportation Institute

TxDOT- Texas Department of Transportation

VMT- Vehicle Miles of Travel

VOC- Volatile Organic Compounds

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CHAPTER I
INTRODUCTION

BACKGROUND

The most commonly cited definition for sustainability and sustainable development is from the Brundtland Commission of 1987, which defined sustainable development as development that meets the needs of the present without compromising on the ability of future generations to meet the same needs. This addresses the key principle of sustainability, namely providing for an uncompromised quality of life in the future. Existing discussion and research on sustainability issues are numerous and varied, but converge on some common themes that must be addressed – environmental and socio-economic issues, and ensuring that possibilities of future development are not limited by present actions.

Transportation plays a major role in today's world and is an essential extension of almost any human activity. Concerns are being raised about the role of transportation in greenhouse gas emissions, fuel resource depletion, toxic pollution, as well as issues relating to transportation costs and the equity impacts of transportation policy. Given this, the study and improvement of transportation sustainability is a logical step toward overall sustainable development.

Concepts of sustainability in transportation have so far been addressed more at the planning and policy-making levels, often as global or national-level initiatives. However, the distinction between addressing sustainability and addressing environmental impacts alone needs to be made.

This thesis follows the style of the *Transportation Research Record.*

The importance of evaluating transportation sustainability as a separate process from conducting environmental impact assessments must be emphasized for the following reasons:

- environmental concerns form only a part of sustainability – the economy, society, and future and current situations also need consideration; and

- transportation itself is a very basic human need, especially in urban areas, and as population grows, so will the demand for transportation. Thus sustainability of transportation systems can contribute greatly to sustainable human development worldwide.

While there has been a certain amount of research attempting to quantify transportation sustainability, there is very little discussion on how to implement the measurement of sustainability within the regular functions of a transportation agency. This is of great significance, especially when the goals of sustainability need to be reconciled with an agency's strategic planning goals. Often, these goals may be not wholly conducive to idealized notions of what is sustainable, but provide a useful starting point to address sustainability.

This research is an attempt to demonstrate how the concerns and concepts relating to sustainability can be incorporated into the planning efforts of any transportation agency, specifically in highway corridor planning applications, through the use of an appropriate performance-measurement based system. Many agencies in the U.S., such as state departments of transportation (DOTs) may not be in a position to exclusively dedicate resources to address transportation sustainability. Sustainability evaluation and enhancement can still be carried out in a scientific, reasonable and logical manner within the general planning paradigm, as a beginning to improving progress toward sustainable development over time.

The ultimate goal of this research is to create a tool that can reflect sustainability concerns in highway planning within the realities and limitations of an agency's operation. Even if this results in a less comprehensive framework than traditionally-proposed sustainability evaluations, the tool is valuable in introducing a new perspective within the transportation planning process.

RESEARCH MOTIVATION

This research was conducted as a part of a sponsored research project for the Texas Department of Transportation (TxDOT). Thus, the development of the sustainability assessment framework was performed based on TxDOT's strategic plan. The methodology developed pertains to highways only, and is designed to work for a given highway section, which has been subdivided into smaller links. The case study for this research was a 15-mile section of US Highway 281 in San Antonio, Texas.

RESEARCH OBJECTIVES

Three main objectives are identified as part of this research in the process of developing a methodology for evaluating highway sustainability. The objectives of this thesis are to:

- develop a framework of performance indicators for evaluating sustainability of a highway section, within the scope of a transportation agency's strategic planning goals;
- create a multi-criteria decision methodology to reflect this framework, appropriately scale the performance measures and combine them into a composite sustainability indicator; and
- evaluate sustainability using the developed methodology for a selected study corridor, considering evaluation scenarios in the present and in the future.

RESEARCH METHODOLOGY

First, the research involved an extensive literature review that covered the basic concepts relating to sustainable transportation. Topics covered included incorporating sustainability goals into the performance-based planning process, performance measures that reflect sustainable transportation, and the state-of-the-practice in terms of transportation sustainability research. General concepts relating to multi-criteria decision making (MCDM) process that could be applied to this particular research topic were also discussed.

Then, a framework for this research (specifically applicable to highways) is developed consisting of performance indicators defined to reflect sustainability, with objectives linking the measures to higher-level strategic planning goals. An MCDM technique was then applied to the sustainability framework to create a methodology for sustainability evaluation. This methodology improves upon previously proposed research in three areas: a) it is developed in a manner that is cognizant of a transportation agency's strategic plan goals, and is designed to address sustainability concerns as well; b) it makes use of local data in an innovative manner, for both the scaling and evaluation of the performance measures, making the methodology context-specific, yet replicable for any other location; and c) the methodology provides a manner in which both current and future development scenarios are evaluated on a common platform – a key aspect of the original conceptualization of sustainability. The methodology developed is then used to conduct a sustainability evaluation case study for a selected test corridor, and the results are presented and discussed in this thesis.

RESEARCH BENEFITS

Sometimes, scientific discussion on sustainability is viewed with skepticism as being of no practical value. This research demonstrates that concepts of sustainability can be incorporated into practical planning, even if the scope becomes slightly narrowed in the process. By targeting a level at which planning is commonly conducted by transportation agencies in the U.S. (highway planning for a single facility), and aligning the process with transportation agency goals, it creates more of a buy-in within the agency than if progress towards sustainability was to be achieved through a separate mandate.

While it can be argued that a better approach would be to redefine agency goals to directly address sustainability concerns, it must be recognized that agency goals are generally set at the highest level in an agency, after much debate and discussion. They represent long term commitments that include political and institutional considerations, and may not be subject to change in the short term.

There is increased recognition of the importance of sustainability, and a trend towards more sustainability-oriented strategic planning in transportation agencies. However, this research is valuable, as addressing sustainability within the planning framework of an agency not only provides immediate assessment of sustainability, but also increases awareness, and can help provide feedback to actually develop more sustainable planning goals in the future.

The development of a detailed methodology for the development and scaling of performance measures used in the MCDM analysis allows the process to be replicated in different contexts. The evaluation of future planning scenarios together with current conditions is also an advantage of this methodology. This research creates a platform for further work on decision-making methodologies, and their implementation in the field of highway planning.

THESIS OVERVIEW

This thesis is divided into six chapters. Chapter I presents an introduction and overview to the research. Chapter II is a literature review that discusses concepts of transportation sustainability, its role in performance-based planning, decision processes associated with sustainability evaluations, as well as existing research efforts related to sustainable transportation. Chapter III deals with defining sustainable transportation within the scope of highway corridors, and creating a framework of performance indicators to the concept. In Chapter IV, an MCDM-based methodology is proposed where the performance measures are quantified, evaluated, scaled, and combined to provide a sustainability assessment. Chapter V is a case study where the methodology is tested as a pilot application for the study section – US 281 in San Antonio, Texas, and the test results are presented. Chapter VI provides concluding remarks, and further discussion of the limitations of the study and prospects for future research.

CHAPTER II
LITERATURE REVIEW

SUSTAINABLE TRANSPORTATION – BASIC CONCEPTS

Sustainable transportation has been the subject of scientific research and discussion over the past decade and earlier (*1*). As a basic concept, sustainability pertains to the recognition, evaluation, and attempted mitigation of long-term impacts of human or developmental activity. Sustainability is predominately discussed in terms of the "three pillars of sustainability," namely: environmental preservation, economic efficiency, and social equity. Additionally, transportation system effectiveness is a fourth criterion that is often considered (*2*).

A recent study of state DOTs in the U.S. (*3*) indicates that while "sustainability" is not explicitly mentioned in the mission and vision statements of most agencies, a majority of them touch upon sustainability concerns by addressing issues such as the environment, future needs, and social equity. Thus, it is clear that state-level transportation agencies are giving importance to sustainability issues, and this research effort is focused on refining methodologies of sustainability evaluation that are relevant at the state level, and can aid in the implementation of a sustainable transportation system.

The assessment of sustainable transportation is generally discussed in three steps– conceptualization, operationalization, and utilization (*4*). Conceptualization deals with defining what sustainability refers to in a particular context, operationalization involves the selection of parameters to measure sustainability, while utilization deals with actually using the findings to guide further development and policy. This paper also discussed two main approaches used when addressing sustainable transportation. In the first approach (considered to be more "metaphorical"), transportation policy is directed to address overarching sustainable development concerns. In the second, sustainable transportation is defined in a more limited sense, as having certain environmental and social constraints. The second approach is considered to be more valuable in terms of practical applications of sustainability evaluation.

ROLE OF PERFORMANCE MEASUREMENT IN EVALUATING SUSTAINABLE TRANSPORTATION

Performance measurement originated as a management tool used by private-sector organizations to evaluate progress toward goals using measurable results or targets (*5*). Performance indicators and performance measures refer to variables that help assess this progress. While the terms are often used interchangeably, some researchers have made the distinction between the two (*4*) – stating that an indicator refers to a variable used in monitoring performance, which becomes a performance measure when compared against standard or benchmark values. While this research does not maintain a strict distinction between the terms, "performance indicator" is used most often while discussing the selection and formulation of attributes to evaluate transportation sustainability, while "performance measure" is used when calculating this attribute for the specific case study, and comparing it to benchmark values. Generally, at the level of a single highway project, the term "evaluation criteria" could also be used while referring to quantified attributes. However, this terminology was not preferred, as the analysis carried out in this research was not necessarily project-specific, but only facility-specific.

With the implementation of the Government Performance and Results Act (GPRA) in 1993, all government agencies in the U.S., including state and local transportation agencies were mandated to use performance measurement, which is when transportation-related performance measures became more commonly used. There exists numerous research and compilations regarding the use of performance measures and their role in the transportation sector in the U.S. over the years (*6, 7, 8, 9*).

A 1997 study of 36 state DOTs conducted to review state-of-the-practice in performance measurement, found that the most commonly used measures were in areas of highway maintenance, safety, highway construction, public transit, and aviation (*6)*.

Fewer numbers of DOTs used performance measures for rail and water transport, and for general administration and organizational effectiveness. However, the research suggested that performance measurement should undergo a paradigm shift to encompass measures of mobility, livability, accessibility, and sustainability.

In keeping with this requirement, there has been significant amount of published research during the past decade relating to transportation sustainability, and the publication of lists of sustainable transportation performance measures. Amekudzi and Jeon (*10*), Litman (*2*), Gudmundsson (*11*), Hall (*12*), and Zietsman (*13*) are examples that provide comprehensive compilations of sustainable transportation indicators used worldwide.

ALIGNING PERFORMANCE MEASUREMENT WITH PLANNING GOALS

Despite the existence of significant research into performance measurement for sustainable transportation, there is an additional issue of implementing the use of these performance measures for transportation agencies. Any performance-measurement based system, be it for organizational management, operational evaluation, or sustainability evaluation still requires some integration with strategic or policy goals (*14*). Research has shown that there are significant benefits to aligning performance measurement with agency policy using a framework of goals, related objectives, and performance measures (*15*, *16*). Therefore, this research examines implementing a performance-measure based sustainability evaluation for TxDOT, within the scope of TxDOT's strategic planning paradigm.

DECISION THEORY – MAUT PROCESS

There are many approaches to decision making in the transportation context, as discussed extensively by Meyer and Miller (*17*). The most structured approach, which is commonly used in environmental decision making, is termed as the "rational actor" approach. This approach aims to attain predetermined goals and objectives in a way that maximizes the utility based on a set of defined evaluation criteria. Operationalizing this approach to decision making is based on decision theory, which is an important field of study in operations research and management-oriented research.

Decision theory deals with creating a means for translating qualitative attributes into a framework that can enable choosing between various alternatives in a scientific manner. It can deal with quantities that are in different units and cannot be equated to each other on monetary or cost-benefit terms. Since qualitative attributes or performance measures are often a part of sustainability evaluations, this approach can compare different criteria based on their "utility" for a set of attributes (which are the indicators or performance measures). This form of analysis was used to evaluate the sustainability of highway corridors (*18*) using a process known as the Multi-Attribute Utility Theory (MAUT). A similar approach was used to evaluate alternative transportation and land use scenarios for the Metro Atlanta Region (*3*). Other sustainability evaluation efforts (*19*, *20*) that are conducted at the global level also make use of utility function values to evaluate sustainability index scores for countries, based on relevant criteria.

The basic methodology common to all the studies cited above (and any other utility-based decision process) can be summarized by the following steps:

1. Selection of criteria and related attributes (performance measures) that reflect sustainability concerns.
2. Quantifying levels of the selected attributes and scaling them to reflect relative preferences based on a "utility function" or "value function."
3. Measuring overall utility of different alternative scenarios based on scaled utility values and relative importance (weights) of the different criteria/attributes.

Keeney (*21*) proved that any multi-factor utility function can be reduced to one that is purely additive or purely multiplicative, and in general, the functions used in an MAUT process are taken to be purely additive in nature. While this provides a clear method for converting qualitative attributes into quantitative measures, this approach does have some shortcomings, largely due to the assumption that all the attributes considered are independent of each other (*22*). This is an inherent shortcoming of the

MAUT-type process. Also, as discussed by Fishburn (*23*), this approach implies that a negative trend on one attribute can be compensated by improving another attribute, which is not intuitively reasonable, especially in the context of environmental concerns and sustainability. However, the proper choice of attributes, and structuring of the utility functions can counter this to a large extent (*24*).

It may be noted that in decision-making applications, “utility function” and “value function” are loosely used as synonyms, referring to a function that translates the levels of a specific attribute into a scaled value representing the desirability of that level. While some authors have objected to the terms being used interchangeably (*25*), this research considers both to have the same meaning.

Scaling of Attribute Utilities in the MAUT Process

In most applications of the MAUT process, the scaling of the utility values is not studied in great detail. It is performed by considering a linear variation of the utility from the “best” to “worst” values, or, as in the case of the study of Metro Atlanta (*3*), values are scaled relative to the best case scenario.

This method of scaling utilities essentially assumes that utility of different alternatives varies linearly with a difference in performance measure value. While this may be acceptable for most performance measures, there could be exceptions. For example, when improving travel times, the value of an initial travel time saving of 5 minutes may be of greater utility than a subsequent savings of an additional 5 minutes, which will not be reflected in the linear utility function. In this research, the process of constructing the utility functions is designed to provide a realistic representation of how the values of various performance measures are perceived to impact highway sustainability. While linear scaling of utility functions may be sufficient for a majority of the performance measures, certain measures may benefit from non-linear scaling. For these, a technique known as the analytic hierarchy process is proposed, as discussed in the following section. Chapter IV addresses in detail the process of the proposed utility scaling.

ANALYTIC HIERARCHY PROCESS

As previously discussed, the construction of utility functions for transportation-related performance measures has not been widely discussed in scientific research. Accorsi et al. (*26*) discussed construction of utility functions for environmental decision making that were based on the Analytic Hierarchy Process (AHP) and linguistic fuzzy sets. The AHP is a technique most commonly used for criteria-weight elicitation in decision making (*27*), though it has a wide variety of applications and methods of implementation. The usefulness of the AHP is in its flexibility that allows modification to a variety of situations that require some level of subjective judgment translation into numerical quantities (*28*). An approach based on the AHP is proposed for constructing selected utility functions in this study. The utilities are based on performance measure data collected for the test corridor, and projected extreme (best/worst case) values. Using the AHP, matrices are constructed based on the relative importance of achieving different attribute scenarios. By linear algebra, the relative incremental utilities of various levels of the attributes were calculated, from which a utility function can be derived.

CONCLUDING REMARKS

Transportation sustainability as a concept is often all-encompassing, which can prove to be a limitation when implementing a methodology to evaluate the concept. While there is a lot of research discussing sustainable transportation, indicators for sustainable transportation, and, more recently, decision-making methodologies to evaluate transportation sustainability, a missing aspect is in aligning the sustainability evaluations to the existing planning framework of a transportation agency. The MAUT has been identified as the most suitable MCDM process, and a refined methodology for implementing it is proposed in this research.

CHAPTER III

EVALUATING HIGHWAY SUSTAINABILITY WITHIN THE TRANSPORTATION PLANNING PROCESS: DEVELOPMENT OF PERFORMANCE INDICATORS

PROBLEM STATEMENT

There is a general consensus among the scientific and professional community that sustainability of transportation systems is of great importance. As discussed in the introductory section, this research seeks to create a model that can be used for highway sustainability evaluation. A 15-mile segment of US 281 in San Antonio, Texas, was chosen as a study corridor to evaluate this methodology. The process of developing a performance-measurement framework for the implementation of sustainability enhancement specific to highways, including the selection of sustainability indicators within the confines of strategic planning goals, is discussed in this chapter.

CONCEPTUALIZING HIGHWAY SUSTAINABILITY

Based on the discussion of findings in the literature review, and the difficulties of changing the direction of strategic planning goals for a transportation agency (as discussed in the introductory section), it can be argued that:

- the range of possible interpretations and definitions for sustainable transportation can sometimes impede progress toward actually implementing assessments of sustainability; and
- when a framework of performance indicators is being used for sustainability evaluation, it is best to align these with the strategic planning goals of the concerned agency.

Therefore, sustainable highway transportation is conceptualized in this research as a highway system that maintains or improves its quality of service while mitigating aspects of highway development that have an adverse effect on sustainability.

Restricting the scope of the sustainability evaluation to a single highway section or corridor – rather than an entire region – has some drawbacks, in that it results in a narrow definition of sustainability. It can be argued that assessing highways only, without consideration of other modes, is in itself antithetical to sustainability. This is supported by the observation that the single most important factor that could lead to a more environmentally sustainable transportation system is the reduction in automobile vehicle miles traveled (VMT) (*29*). However, it is of value to reconcile sustainable planning with the realities of transportation in the U.S. – the personal automobile is the most commonly used form of transportation for all types of trips, and consequently, a majority of the work carried out by state DOTs involves highway corridor planning. While considering a single highway for the analysis creates a lack of demographic, equity, and employment data that could prove useful for sustainability evaluations in the more traditional sense, the value of this exercise lies in being able to link sustainability to the existing planning process.

Linking Sustainability to TxDOT's Strategic Plan

This research was conducted creating sustainability awareness among state agencies, as a part of a study seeking to link sustainability to a transportation agency's planning goals, and forming the basis for more integrated transportation planning in the future. The rationale behind this is that transportation planning is inherently political in nature and that implementing a sustainability assessment within already-defined planning goals would result in it being given greater importance and raising awareness. Thus, the sustainability indicators selected for this research were aligned with TxDOT's strategic plan.

TxDOT's Strategic Plan for 2007-2011 (*30*) is a document outlining the mission, vision, and goals for the entire agency. There are five specific goals identified and discussed in the strategic plan:

- Reduce Congestion;
- Enhance Safety;

- Expand Economic Opportunity;
- Improve Air Quality; and
- Increase the Value of Transportation Assets.

The main challenge of this project was to develop a set of performance indicators that reflected sustainability concerns within the scope of the strategic plan. To facilitate this, a workshop was held with key TxDOT personnel, representing stakeholders and potential users of the final research product. Workshop participants discussed how the dimensions of sustainability – economic development, environmental stewardship, and social equity – could be applicable to progress toward the goals. Initially, to facilitate ideas and discussion, the five goals were classified under the most appropriate "sustainability dimension" (environmental, economic, and social). Following this, a set of objectives were defined under each of the strategic goals, and each objective was linked to a measurable indicator that could be used in the sustainability evaluation. Figure 1 shows the steps involved, including further steps of defining, quantifying, and evaluating the performance measures.

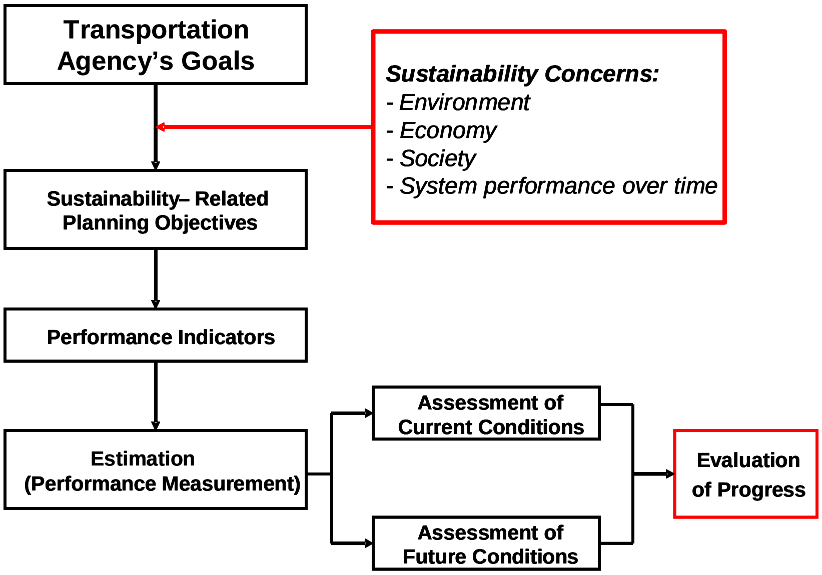

Figure 1. Conceptualization: Linking Sustainability to Planning Goals.

Table 1 presents a listing of TxDOT’s goals, along with the sustainability-related objectives defined for each goal. When the goals and objectives were initially classified according to their sustainability dimensions category, it was observed that a majority of the objectives address more than one aspect of sustainability. Therefore, rather than classifying each objective based on what facet of sustainability it addresses, the motivation for selecting particular objectives and the process of defining performance indicators for each is discussed.

Table 1. Sustainability-Related Objectives to Address TxDOT's Strategic Plan.

Strategic Goal	Sustainability-Related Objective
Reduce Congestion	Improve mobility on highways
	Improve reliability of highway travel
Enhance Safety	Reduce crash rates and crash risk
	Improve traffic incident detection and response
Expand Economic Opportunity	Optimize land use mix for development potential
	Improve road-based freight movement
Increase Value of Transportation Assets	Maintain existing highway system quality
	Reduce cost and impact of highway capacity expansion
	Leverage non-traditional funding sources for highways
	Increase use of alternatives to single-occupant automobile travel
Improve Air Quality	Reduce adverse human health impacts
	Reduce greenhouse gas emissions
	Conform to emissions exposure standards

DEVELOPMENT OF PERFORMANCE INDICATORS

This section discusses the development of a set of indicators for use in evaluating progress toward each of the objectives defined. These indicators, when appropriately quantified and benchmarked, become performance measures that can be incorporated into the multi-criteria assessment methodology. The list of objectives in Table 1 show that alternatives to automobile use are sometimes not explicitly considered. To counter this, the performance indicators that address each objective are defined such that an excess of VMT is “penalized.” As discussed previously, the most significant step towards transportation sustainability can be achieved through reduction of automobile VMT. Thus, the performance indicators are selected and structured to reflect the negative impact increased VMT has on sustainability. This chapter provides a detailed discussion of the reasons for selecting particular objectives, and the development of performance indicators related to each of TxDOT’s strategic plan goals. The calculation procedures and data elements required to evaluate these as performance measures are discussed in the next chapter.

Goal 1: Reduce Congestion

This goal is fairly self-explanatory, and addresses the need for reducing traffic congestion on highways. Congestion reduction can have benefits in terms of saving time, lowering emissions and fuel consumption, as well as impacting safety. While a partial solution to congestion is adding highway capacity, political and institutional realities in the recent past have shown that this is not a practical solution. Congestion management and mitigation is also significant from a system effectiveness standpoint, especially when comparing alternative scenarios, or considering future increases in traffic.

Thus, maintaining or improving upon levels of congestion over time is desirable – as it can indicate reduced VMT and a reduced requirement for highway capacity expansions. Table 2 shows the objectives and indicators proposed for this goal. These cover the two aspects that are generally considered when referring to traffic congestion – the first addresses the actual travel time increases caused by congestion, while the second examines how it affects the reliability of travel assessed over a longer time frame.

Table 2. Performance Indicators for Goal 1: Reduce Congestion.

Sustainability-Related Objective	Performance Indicator
Improve mobility on highways	Travel Time Index
Improve reliability of highway travel	Buffer Index

Both of the selected indicators are used for congestion monitoring in the Texas Transportation Institute's (TTI) *Urban Mobility Report* (*31*). The following sections discuss these measures individually.

Travel Time Index

The Travel Time Index is a measure that indicates the extent of delays caused in travel due to traffic congestion alone. It is generally quantified as a ratio between the peak period travel times and off-peak travel times for a given roadway section.

Buffer Index

The Buffer Index is an indicator of travel time reliability that provides an estimate of the variation of observed travel times over a period of time. It indicates the extent to which the 95th percentile travel time for a roadway exceeds the mean travel time. In the absence of long-term data to judge the distribution of travel times for a given roadway, there are also empirical relationships derived between the Travel Time Index and Buffer Index that can be used to estimate the Buffer Index values. This relationship has been used in this research, and is provided in the next chapter.

Goal 2: Enhance Safety

This goal is mainly concerned with fatalities or crashes that result in severe injuries. With respect to this goal, two objectives are laid out. The first is to reduce crash frequency and crash risk, while the second relates to having surveillance systems in place for monitoring traffic and incident response. Achievement of these objectives has significant benefits – in terms of both human lives saved and the economic costs of crashes. Having Intelligent Transportation System (ITS) facilities such as traffic surveillance and incident response is also beneficial from a safety perspective. Additionally, ITS facilities can aid congestion monitoring and in emergency evacuations. Table 3 shows the two performance indicators to address these objectives and their formulation.

Table 3. Performance Indicators for Goal 2: Enhance Safety.

Sustainability-Related Objective	Performance Indicator
Reduce crash rates and crash risk	Annual severe crashes per mile
Improve traffic incident detection and response	Percentage lane miles under traffic monitoring/surveillance

Annual Severe Crashes per Mile

Crashes are most commonly expressed as a crash rate (the number of crashes per million vehicle miles traveled [MVMT]), a statistic that allows for comparison of crashes between different locations, while accounting for the differences in levels of travel in the locations. The use of a crash rate, however, does not account for the increased number of crashes resulting from increased VMT. This is an important consideration from a sustainability perspective; therefore, the indicator considered here is the severe crash frequency per mile of highway. To evaluate this measure, crash prediction models are used that consider traffic volumes, basic geometrics of the roadway, roadway type, and other design features. The annual frequency (crashes per mile) of severe crashes – defined as fatal crashes or those resulting in injury – is estimated by the prediction model. The calculations are based on procedures outlined in the *Interim Roadway Safety Design Workbook* (*32*), and are discussed further in the next chapter.

Percentage Lane-Miles under TMC Surveillance

This measure estimates the presence of ITS, including traffic monitoring and emergency response facilities in terms of coverage of a highway section by a Traffic Monitoring Center (TMC). This coverage is expressed in terms of percentage of the total lane-miles.

Goal 3: Improve Economic Opportunity

In TxDOT's strategic plan, this goal addresses trade opportunity, freight movement, faster deliveries, and enabling transportation to serve local trade, job opportunities, and businesses. From the perspective of sustainability and long-term economic viability, the mixing of land uses can be beneficial, and is one of the objectives defined. Another aspect of job and business vitality is freight movement, which is also addressed as an objective. Table 4 shows the performance indicators selected for these objectives.

Table 4. Performance Indicators for Goal 3: Improve Economic Opportunity.

Sustainability-Related Objective	Performance Indicator
Optimize land use mix for development potential	Land use balance
Improve road-based freight movement	Truck throughput efficiency

Land Use Balance

This measure is a formulation that examines a mix of land uses in a half-mile zone along the highway section. The land area is classified into three categories: Residential, Commercial/Industrial, and Institutional/Public. The measure is similar to the estimation of land use entropy used to evaluate diversity of land use in a region, proposed by Cervero and Kockelman (*33*). It is formulated to have the highest value when all categories of land use are equally distributed and the lowest values when all the land uses are concentrated into any one category. While this measure does not explicitly examine economic growth or progress, the presence of an adequate area devoted to commercial establishments balanced with residential land use types ensures a positive impact on economic vitality of an area, when compared to having land occupied by a single land use, or land that is completely vacant. It can be argued that having a mix of land uses around a highway does not necessarily reflect the true characteristics of the mix in terms of accessibility or walkability (which are important sustainability concerns), and may promote sprawl. However, these aspects cannot be addressed given the scope of analysis, and it is felt that the area for which this measure is evaluated (half a mile to either side of the highway) is large enough to benefit from having a level of non-homogeneity in land uses, which will also reflect in the use of the highway under consideration.

Truck Throughput Efficiency

This measure is a reflection of truck volumes along the highway section, combined with the travel speeds on the links. Freight movement is a key economic benefit of highways, and the objective in this analysis is to maximize freight throughput without affecting highway performance. The theory behind this measure is that the impact of having trucks in terms of economic benefits should be measured in a way that accounts for possible reductions in travel speeds due to excessive truck volumes, or existing low speeds along the corridor. Thus, a measure that examines a combination of truck volumes and speeds as an output, rather than truck percentages alone is proposed.

Goal 4: Increase the Value of Transportation Assets

This goal seeks to reduce the impacts of declining fuel tax revenue on the existing highway infrastructure, and on the possibility of new highway projects. The focus is on preserving and maintaining existing assets, while leveraging the maximum possible funding from all available sources.

While defining objectives for this goal, the approach was to consider more sustainable ways of improving and maintaining TxDOT’s existing highway system. First, the quality of existing highways should be maintained. Second, leveraging of non-traditional funding sources for highways can help free up state DOT funds to promote other modes of transportation. When alternative funding encompasses tolled roads, it could indicate that a greater portion of true user costs is being paid for by automobile users themselves (*34*). Another objective examines mitigating the impact of highway capacity expansion. While expansion can often be desirable from the point of view of easing traffic congestion, there are negative externalities associated with it in terms of the actual costs and impacts of the land acquisition and construction. The final objective deals with the provision of other mobility options, which can also include non-single-occupant vehicle (SOV) automobile travel. Table 5 shows the performance indicators addressing this goal and the objectives.

Table 5. Performance Indicators for Goal 4: Increase Value of Transportation Assets.

Sustainability-Related Objective	Performance Indicator
Maintain existing highway system quality	Average pavement condition score
Reduce cost and impact of highway capacity expansion	Capacity addition within available right of way
Leverage non-traditional funding sources for highways	Cost recovery from alternative sources
Increase use of alternatives to SOV automobile travel	Proportion of non-SOV travel

Average Pavement Condition Score

TxDOT monitors the condition of the pavements in the road network by considering factors such as surface distress, rutting, and ride quality. The data for the entire network is collected in a Pavement Management Information System (PMIS), which combines these factors into a pavement condition score expressed on a scale of 0-to-100. This is proposed as a performance measure that indicates the quality of maintenance of a road section.

Capacity Expansion Possible within Available Right-of-Way

While having increased highway capacity could be beneficial from the standpoint of improving the value of the highway system, there are reasons why simply adding miles of pavement is not completely sustainable. This measure addresses the issue by only considering expansion that is possible within existing right-of-way (ROW), which represents value addition at a lesser social, environmental, and economic cost than acquiring land solely for the purpose of highway construction. Though the impact of increased traffic due to a capacity expansion is not reflected in this performance measure, it will affect the value of other measures relating to congestion levels, crash numbers, and emissions rates. Thus, capacity expansion within certain constraints can be an indication of highway sustainability, and is measured in terms of the number of lanes that can be added to a given highway section within the available ROW.

Cost Recovery from Non-DOT Sources

The expenditure on a highway can be classified as the initial capital cost required for construction, and the recurring (annual) cost for operation and maintenance (O&M). When some of these costs are contributed from sources external to the DOT, it can be considered a positive occurrence, as discussed previously. This performance measure is structured to consider the proportion of capital costs, as well as the proportion of the current annual O&M cost that is contributed from external sources. In this research, external sources are considered to include funds from local/municipal agencies, toll revenue recovered, or roads that are built or operated by the private sector.

Proportion of Person Miles of Travel Occurring in Non-SOVs

The rationale behind selecting this measure (as an indicator of reducing overall VMT) has been discussed previously. It evaluates the higher occupancies achieved by carpooling, use of bus transit or parallel rail facilities. This measure is calculated by accounting for non-SOVs in the general purpose lanes, high-occupancy vehicle (HOV) lanes, buses, and parallel rail facilities.

Goal 5: Improve Air Quality

This goal specifically addresses air quality, which is a major concern, especially in urban areas. The U.S. Environmental Protection Agency (EPA) has set out standards for air quality. The National Ambient Air Quality Standards (NAAQS) and the regulation of motor vehicle emissions are very important to achieving those standards. While evaluating air quality alone does not address the whole gamut of environmental issues associated with road transportation, motor vehicle emissions are considered as the most significant issue for an existing highway. In terms of emissions, the impacts can be broadly divided into two aspects – first, toxic pollutants and ozone precursors that affect human health, and second, emissions of greenhouse gases. Each of these is addressed by an individual objective The emissions monitoring programs in the state of Texas generally consider the emissions of carbon monoxide (CO), oxides of nitrogen (NO_x), and volatile organic Compounds (VOCs) in terms of human-health impacts. CO is a toxic gas that is lethal to humans; while NO_x and VOCs are considered as ozone precursors (they create ozone in the presence of sunlight). Ozone, when present in the lower levels of the atmosphere, also causes respiratory problems for humans.

Though the state of Texas does not ordinarily consider carbon dioxide (CO_2) emissions as part of its environmental monitoring or mitigation program, it was felt that addressing CO_2 emissions was a necessary part of a sustainability evaluation, given the growing concern about greenhouse gases and the ultimate impacts of global warming. The final objective relating to this measure examines the impact of air quality in terms of exposure levels that cause harm to humans and the environment. It considers problem areas that represent the “worst case” for emissions exposure in terms of the NAAQS. Table 6 shows the performance indicators developed for each of these objectives.

Table 6. Performance Indicators for Goal 5: Improve Air Quality.

Sustainability-Related Objective	Performance Indicator
Reduce adverse human health impacts	Daily NO_x, CO, and VOC emissions per mile of roadway
Reduce greenhouse gas emissions	Daily CO_2 emissions per mile of roadway
Conform to emissions exposure standards	Attainment of ambient air quality standards

Daily NO_x, CO, and VOC Emissions

NO_x, CO, and VOCs are the mobile-source emissions usually considered in terms of human-health impacts. The rate of emissions for a vehicle depends upon the operating speed and varies by vehicle type. These rates can be obtained from emissions estimation models (MOBILE6 – the EPA's model is used in this research). For the purposes of this study, the total quantity of emissions is expressed in grams per mile of roadway, which is dependent upon the vehicle fleet mix, vehicle operating speed, as well as the total traffic volumes. The final measure is the sum total of the three pollutant emissions, weighted according to their relative damage costs.

Daily CO_2 Emissions

CO_2 is a gas emitted from burning fossil fuels, which is associated with global warming. Vehicular emissions are the most significant anthropogenic source of CO_2 (*29*), and these must be considered while assessing the sustainability of transportation systems. Emissions rates are obtained from an emissions model, as in the previous measure, and are expressed as the daily emissions of CO_2 in grams per mile of roadway.

Attainment of Ambient Air Quality Standards

While the other two performance indicators addressing air quality provide an idea of the relative levels of emissions, this measure examines the actual impact in terms of attainment of ambient air quality standards. As mentioned earlier, the EPA sets out standards for air quality for certain "criteria pollutants," as specified in the NAAQS. The levels of these pollutants are monitored regularly. Based on the duration and level of non-conformance, a region can be classified as being in nonattainment for specific pollutants. Since the ambient air quality does not depend solely upon automobile emissions, but is also affected by industries and other sources of pollution, the attainment status for a region cannot be directly correlated to automobile emissions, or estimated in the future.

This performance indicator is developed to address this for the case of ozone nonattainment, which is a problem faced by many counties in Texas. As mentioned earlier, NO_x and VOC represent ozone precursors, whose emissions can be linked to increased levels of ozone. This performance indicator attempts to address this link by examining two factors – first, the current level of attainment of ozone standards (whether in attainment, or in marginal, moderate, severe, or extreme nonattainment); and second, the estimated levels of VOC and NO_x emissions. Thus, the performance indicator is quantified as a score based on the current level of nonattainment for ozone according to the NAAQS. For the evaluation of a future case (where the attainment status cannot be predicted), this score is adjusted based on the relative level of reduction in ozone precursor (combined NO_x and VOC) emissions.

CONCLUDING REMARKS

Many sustainability indicators are not practically implemented at the highway corridor level, but can be more easily considered at the aggregate level (of a county/city). Examples of this include measures of equity such as employment access or income distributions. Given the constraints of restricting the evaluation to highway segments alone, it is felt that the performance measures selected are adequate, without being impractical to evaluate. Another aspect of sustainability that is also captured in this research effort is the consideration of changes over time. Future and present conditions are evaluated on a common ground, rather than making allowances or accepting that future conditions would be worse. This is a key sustainability concern (i.e., future conditions should be better than today) that has been addressed. The references for sustainable transportation indicators mentioned in the literature review (*2, 10, 11, 12, 13*) provide a comprehensive listing of resources and indicator sets that relate to sustainable transportation. These references show that the indicator set proposed here provides a fairly complete view of issues that need to be addressed in terms of sustainability. The following chapters deal with the quantification of these performance measures, their combination into an aggregate sustainability indicator, and the application of this evaluation methodology to a case study.

CHAPTER IV

MAUT-BASED METHODOLOGY FOR HIGHWAY SUSTAINABILITY EVALUATION

APPLICATION OF MAUT METHODOLOGY

As previously discussed, the framework for performance-based evaluation of highway sustainability has been developed to assess a single section of highway. As seen in the previous chapter, the analysis does consider corridor-level information such as parallel rail facilities, or land use. However, the term “section” is used to describe the level of analysis, as a corridor can include multiple parallel road facilities, whereas this research only discusses a single facility and its impact. The section under consideration is divided into smaller links, and the calculation methodology can be applied to individual links, as well as to the aggregate highway section. Figure 2 shows a schematic setup. Thus, the results for a specific link are comparable with any other link, or with the entire section. This allows for the identification of problem areas on a given section, and to determine how each link measures up compared to the average. Also, this assessment can be used to compare different highways or different proposed projects for a single highway.

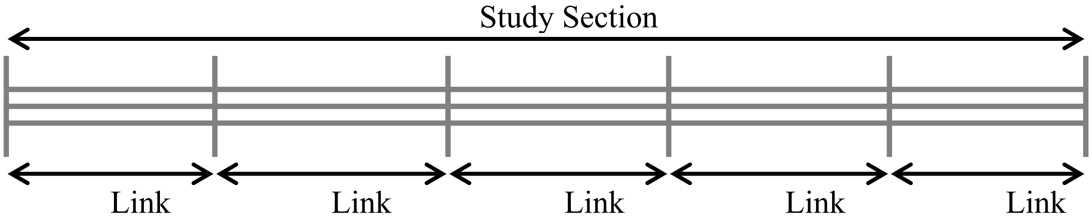

Figure 2. Setup of Links and Sections for Multi-Criteria Analysis.

The selected performance indicators described in the previous chapter are to be quantified, scaled, and aggregated into a final index value representing the result of the sustainability evaluation.

Translating Performance Indicators to Performance Measures

The distinction between a performance indicator and performance measure in this research has been discussed in the literature review –when sustainability indicators are quantified and benchmarked for a specific evaluation, they become performance measures. The sustainability indicators proposed in the previous chapter are quantified as performance measures as the first step in the MAUT methodology. Figure 3 shows the steps involved in this process. Each of these steps is performed for individual links, as well as for the aggregated study section. The process of performing each of these steps is discussed in this chapter.

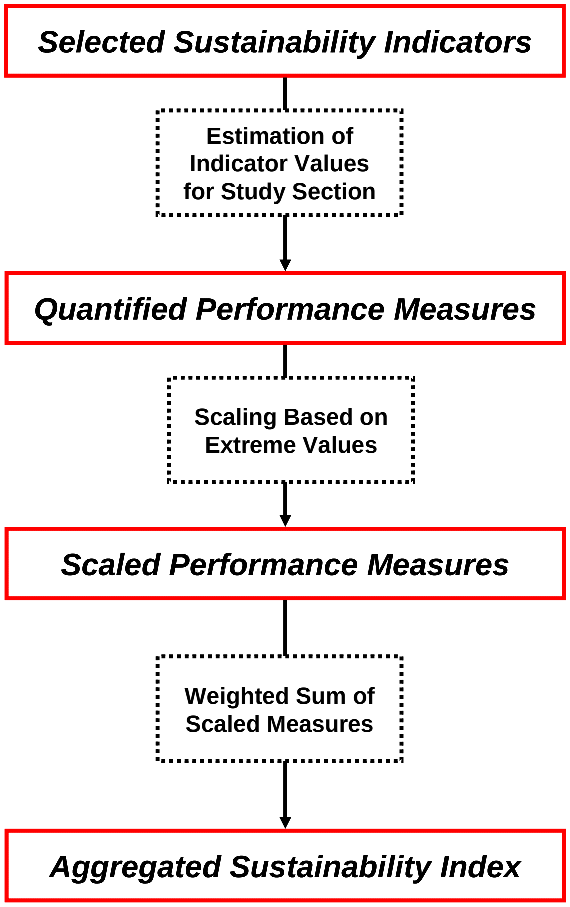

Figure 3. MAUT Process for Sustainability Evaluation.

QUANTIFICATION OF MEASURES AND EXTREME VALUES

Data Elements and Estimation Procedures

The previous chapter detailed the rationale for selecting the particular performance indicators, and the general procedures used to evaluate them. Table 7 provides a summary of the performance measures, the data elements required to quantify them, and the units of expression for each performance measure. Each of these measures is evaluated for the existing conditions, as well as for a projected future scenario.

Based on the data elements, the performance measures can be quantified for individual links and for the overall study section. The estimation processes are explained in this chapter, while the next chapter provides illustrative examples for the calculations.

Definition of Extreme Values for the Selected Measures

Each of the performance measures discussed in the previous section need certain benchmark values for comparison, to indicate the performance measure’s value – good or bad. This is expressed by the “scaling” or “normalizing” of the performance measure. To perform the scaling, however, it is necessary to define two extremes that represent the best and worst possible values for a given performance measure. These extreme values are defined to represent plausible scenarios relating to the performance measure, and not necessarily the theoretical maximums or minimums. The selection or calculation of these extreme values to be used for scaling each of the measures is also discussed in this section.

Table 7. Data Elements for Quantification of Performance Measures.

Reference Number	Performance Indicator	Data Elements for Quantification	Unit
1a	Travel Time Index	Daily volumes (ADT) Number of lanes Speed limits	Dimensionless
1b	Buffer Index	Travel Time Index	Percentage
2a	Annual severe crashes per mile	Roadway type ADT Geometrics	Severe crashes per mile per year
2b	Percentage lane miles under TMC surveillance	Whether individual link is monitored by a TMC	Percentage of total lane-miles
3a	Land use balance	Area allocated to different land use classifications in zone half-mile to either side of highway section	Dimensionless
3b	Truck throughput efficiency	Truck percentages Daily traffic volumes Number of lanes	Truck-miles per hour per lane
4a	Pavement condition score	Score from TxDOT's PMIS database	Dimensionless
4b	Capacity addition within ROW	Number of lanes that can be added to a link within available ROW	Number of lanes
4c	Cost recovery from alternate sources	Project capital costs and sources Annual operating and maintenance costs and sources	Dimensionless
4d	Proportion of total person-miles of travel for non-SOVs	ADT GPL occupancy HOV lanes and usage Details of bus and rail service	Percentage of total PMT
5a	Daily NO_x, CO, and VOC emissions in grams per mile	Emissions rates (emissions model) Peak and off-peak volumes Operating Speeds	Grams per mile per day
5b	Daily CO_2 emissions in grams per mile	(As above)	Grams per mile per day
5c	Attainment of ambient air quality standards	Classification for NAAQS eight-hour ozone standards Ozone precursor emissions	Dimensionless

Travel Time Index

The Travel Time Index value is quantified as the ratio of peak-period travel time to travel times corresponding to the posted speed limit, as Equation 1 shows.

$$Travel\,Time\,Index = \frac{Peak\ Hour\ Travel\ Rate\,(Minutes\ per\ Mile)}{Travel\ Rate\ at\ Posted\ Speed\ Limit\,(Minutes\ per\ Mile)} \qquad (1)$$

To estimate the peak-period speeds, the procedure outlined in TTI's *Urban Mobility Report* (*31*) is used. This procedure calculates peak-period vehicle operating speeds based on the average daily traffic (ADT) per lane. Equations 2 through 5 show the speed estimations.

For ADT/Lane= 15001-17500,

$$Peak\text{-}Period\ Speed = 70-(0.9 \times ADT/Lane) \qquad (2)$$

For ADT/Lane=17501-20000,

$$Peak\text{-}Period\ Speed = 78-(1.4 \times ADT/Lane) \qquad (3)$$

For ADT/Lane = 20001-25000,

$$Peak\text{-}Period\ Speed = 96-(2.3 \times ADT/Lane) \qquad (4)$$

For ADT/Lane >25000,

$$Speed = 76-(1.46 \times ADT/Lane) \qquad (5)$$

In the preceding calculations, the speeds corresponding to an ADT per lane less than 15,000 are estimated as the posted speed limit. The lower limit for speed calculations in this procedure is 35 mph. Based on the estimated peak-period speeds, the peak-period travel times for each of the links can be calculated. The travel times corresponding to the posted speed limit are also calculated, and the Travel Time Index value for each link is obtained. The Travel Time Index value for the entire section is calculated as the average for each link, weighted by the VMT on each link. Figure 4 shows the steps involved in estimating the Travel Time Index.

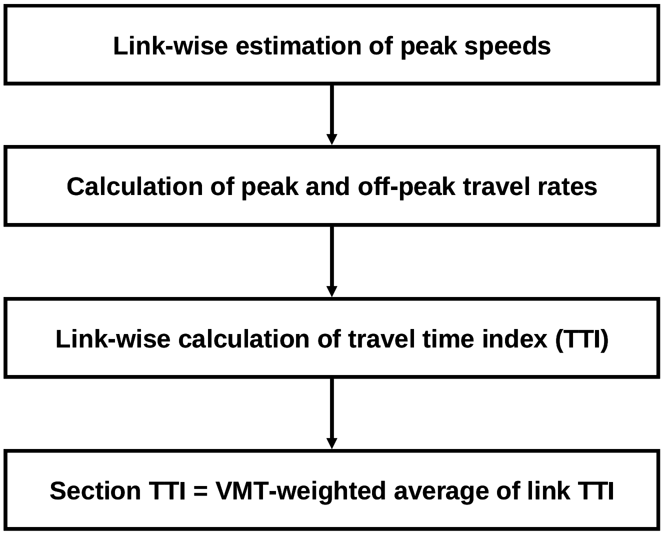

Figure 4. Estimation Process for Travel Time Index.

Extreme Values

For the Travel Time Index, a best case scenario is represented by a value of 1.0, indicating peak-period travel that is not delayed by congestion. In this research, the worst case scenario is defined as a Travel Time Index value of 1.5. While the Travel Time Index can exceed 1.5 (and does so for specific facilities in most urban areas), this value is selected as the maximum, as it represents the worst case scenario in the U.S. – the city of Los Angeles (*35*). It should be noted that the *Urban Mobility Report* estimates area-wide mobility statistics that include off-peak traffic conditions, and this estimation methodology results in lower values of the Travel Time Index.

Buffer Index

The Buffer Index value is calculated based on the distribution of travel times for a given section of roadway over a period of time (day-to-day or month-to-month), indicating the extent to which the highest travel times exceed the average. Equation 6 shows the formula for the Buffer Index.

$$\mathit{Buffer\ Index} = \frac{95th\ \mathit{Percentile\,Travel\,Time}\,(\mathit{Minutes}) - \mathit{Average\,Travel\ \ Time}\,(\mathit{Minutes})}{\mathit{Average\,Travel\ \ Time}\,(\mathit{Minutes})} \qquad (6)$$

A high Buffer Index indicates unreliable travel conditions, and generally has some correlation with higher congestion levels and Travel Time Index values. An empirical relationship between the Buffer Index and the Travel Time Index has been developed by the Texas Transportation Institute from data where real-time data are available. This relationship, valid for Travel Time Index values up to 1.5, is used to estimate the Buffer Index, and is presented in Equation 7.

$$\mathit{Buffer\ Index} = 2.189 \times (\mathit{Travel\ Time\ Index}-1) - 1.799 \times (\mathit{Travel\ Time\ Index}-1)^2 \qquad (7)$$

As with the Travel Time Index, the Buffer Index is estimated for each individual link. The Buffer Index for the entire section is calculated as the average for all links, weighted by the total VMT for each link.

Researchers continue to evaluate the relationship between Travel Time Index and Buffer Index. Existing data are limited to instrumented freeway locations in the United States, with calibrated sensors. Due to the variability of the Buffer Index for a given Travel Time Index, it is important to recognize there is typically a range of values for a given Travel Time Index. The average value is used here to facilitate estimation for this sustainability example.

Extreme Values

The best and worst case extremes for the Buffer Index are the values corresponding to the best and worst case for the Travel Time Index. Thus, the best case is a Buffer Index value of 0, and the worst case corresponds to a value of over 0.65.

Annual Severe Crashes per Mile

The crash estimation procedure is based on the *Interim Roadway Safety Design Workbook* (*32*). The procedure for calculating total number of crashes accounts for the roadway type, length, ADT, and number of lanes. Using this, a base crash frequency (annual severe crashes) is calculated. Then, accident modification factors for features such as the grade, lane width, shoulder width, and median type are applied to this base crash frequency to obtain the total number of annual severe crashes. In the case of roads that have at-grade access, crash estimations for intersections is performed and added to the roadway crash frequency. This total crash frequency is then divided by roadway length to obtain the final performance measure. This process is performed for each link, and is summarized in Figure 5. The performance measure for the entire section is calculated as the average for the individual links, weighted by link lengths. Appendix A presents the formulas and details of the crash estimation methodology and accident modification factors used.

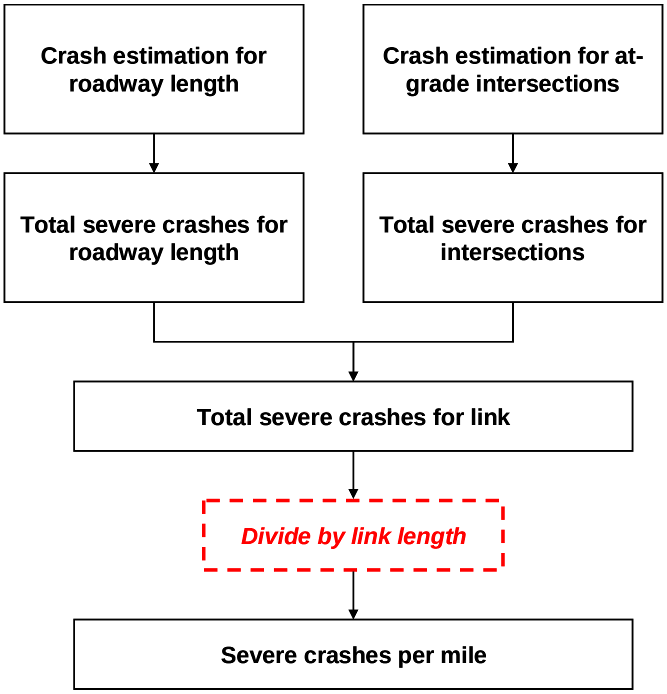

Figure 5. Crash Estimation Process for Each Link.

Extreme Values

For this measure, the best and worst case values were determined based on crash frequency datasets for a three-year period in the U.S. Based on detailed analysis of the data set, Table 8 shows the suggested extreme values for different road classifications and the proposed number of lanes. Appendix A also presents the scatter plots of the data used to determine these scaling values.

Table 8. Extreme Values for Annual Crashes per Mile.

			Annual Severe Crashes per Mile	
Road Type	**Sub Category**	**Lanes**	**Best**	**Worst**
Freeways	Rural	4 Lanes	0	5
		6 Lanes	0	8
	Urban	4 Lanes	0	15
		6 Lanes	0	23
		8 Lanes or More	0	35
Rural Highways	Depressed Median	4 lanes	0	5
		6 lanes	0	6
	Undivided/Surfaced Median	2 lanes	0	2
		4 lanes	0	6
Urban Streets	All	2 Lanes	0	20
		4 Lanes	0	20
		6 Lanes	0	20

Percentage Lane Miles under TMC Surveillance

At the link level, this performance measure can only have a value of 0 percent or 100 percent, depending on whether the link is monitored by a TMC. For the entire section, the measure is calculated based on the lane miles for all links with TMC surveillance, to total lane miles of the section.

Extreme Values

For this measure, the presence of TMC surveillance on the entire study section is considered desirable, thus the best case scenario has a measure value of 100 percent. The worst is a measure value of 0 percent, indicating no TMC monitoring or surveillance.

Land Use Balance

Evaluation of this measure requires data on the land use for a zone half-mile to either side of the link under consideration. The land use classifications are three categories as follows:

1. Residential;
2. Commercial/Industrial; and
3. Institutional/Public.

Equation 8 shows the formula for measuring land use balance.

$$\textit{Land Use Balance} = \frac{\sum P_i \times \ln P_i}{\ln N} \qquad (8)$$

Where,

$P_i =$ the proportion of total land area allocated to each land use classification; and

$N =$ total number of land use categories considered (N=3 in this research).

The area of land currently occupied by each of these uses is considered for this measure, and may be obtained using Geographic Information Systems (GIS) maps or data. For future scenarios, the areas can be calculated based on a future land use plan. In the absence of a land use plan for the region, appropriate assumptions may be made based on growth patterns and the general direction of development. This measure is calculated by applying the formula for individual links, as well as for the entire section.

Extreme Values

The calculation of this measure results in a value of 0 when a single land use classification occupies the entire area, while the measure equals 1 when equal land areas are allocated to each land use type. Thus, the best and worst case scenarios for this measure are defined as 0 and 1 respectively.

Truck Throughput Efficiency

The truck throughput efficiency (TTE) is calculated as the product of daily truck volumes per lane and the truck operational speed, as Equation 9 shows.

$$TTE = \text{Daily truck volumes per lane} \times \text{Truck operational speed} \tag{9}$$

The calculation for this measure is based on truck percentages, total daily traffic volumes per lane, and the operational speeds for trucks. Research indicates that trucks, on average, travel 6 percent slower than passenger cars in the traffic stream (*36*). Thus, a reduced truck operational speed was considered. This performance measure is estimated for individual links, and the length-weighted average of these measures is calculated as the section's performance measure.

Extreme Values

The performance measure is estimated for a range of traffic volumes, for truck percentages incremented from 2 percent (considered a plausible minimum)-to-20 percent (considered a desirable maximum). Based on the range of performance measure values generated, the best and worst case scenarios were identified as 170,700 and 5,600 daily truck miles per hour per lane, respectively. Appendix B shows the calculation of these extreme values and the process of optimizing this measure.

Pavement Condition Score

This score is obtained from TxDOT's PMIS database and is expressed on a scale of 0-to-100. Thus, the best case scenario for this measure is a score of 100, while the worst corresponds to a score of 0. However, this score cannot be predicted for the future. It is assumed that in the case of any capacity addition in the future, an improved pavement quality is expected and the score assigned accordingly. Otherwise, depending upon knowledge of DOT funding sources, and the existing maintenance routines, the score in a future situation can be estimated.

Capacity Addition within Available ROW

As discussed previously, this measure is quantified based on the number of lanes that can be added within the available ROW for each link. This represents a set of possible whole number values, on which a score is based and assigned as the final performance measure for each link. Table 9 shows the scoring for this measure. The performance measure for the aggregate section is then calculated as the average of the individual links' scores, weighted by their lengths. The feasibility of adding lanes within the ROW according to standard engineering practice can be assessed using GIS or physical inspection of the area.

Table 9. Scoring for Capacity Addition Measure.

Possible Lane Addition within ROW	Score Assigned
None	0
1	0.25
2	0.5
3	0.75
4 or more	1

Extreme Values

The best case scenario is a performance measure value of 1, corresponding to the possibility of adding four or more lanes within available ROW. The worst case scenario, corresponding to a measure value of 0, is when no lane additions are possible within available ROW.

Cost Recovery from Alternate Sources

This performance measure is evaluated on a link-wise basis, based on the contribution of alternate sources to capital expenditures and O&M expenditures for a given roadway section. Because this indicator is constructed as a sum of the proportion of cost recovery for capital expenses and O&M expenses, the definition of an "alternate source" is flexible, as long as it is used consistently. For the purposes of this analysis, alternative sources are defined as local government agencies, private sector funding, or toll revenue. Equation 10 shows the estimation procedure.

$$External\ Cost\ Recovery = W_{cap} \times \left(\frac{Capital_{ext}}{Capital_{tot}} \right) + W_{O/M} \times \left(\frac{O\,\&\,M_{ext}}{O\,\&\,M_{tot}} \right) \qquad (10)$$

Where,

W_{cap} *and* $W_{O\&M}$ = weights (adding to 1) allocated based on the importance of capital recovery versus operating costs recovery;

$Capital_{ext}$ = capital costs contributed by external sources for the highway section being analyzed;

$Capital_{tot}$ = total capital costs for the highway section being analyzed;

$O\&M_{ext}$ = amount contributed from external sources to current annual O&M expenditure for the highway section being analyzed; and

$O\&M_{tot}$ = total current annual O&M expenditure for the highway section being analyzed.

In the case of O&M costs, recovery of the most recent annual expenditure is considered. However, for the capital expenditure, if major investments have occurred at different years, the costs are translated to present value before examining the proportion of overall capital recovery.

The recovery proportions for capital expenses and O&M expenses are combined as a weighted sum to quantify the final performance indicator. In this analysis, a higher weight is given to O&M expense recovery than to capital expenditure recovery (60 percent-to-40 percent). This is because increasing maintenance costs are of greater concern to DOTs, as they are recurring expenses that often require a majority of available funding. However, this weight allocation may be adjusted according to local priorities as necessary. This measure is assessed for each link, and the performance measure for the entire section is defined as the length-weighted average of the measure for individual links.

Extreme Values

This performance measure has a value of 1 when the entire capital and operating expenses for a link or section are recovered from alternate funding sources, and a value of 0 when no expenses are recovered. Thus, the best and worst case scenarios for this measure are defined as 1 and 0, respectively.

Proportion of Total Person-Miles of Travel in Non-SOVs

The automobile is the most common mode of transport in the U.S., with SOV travel being the most prevalent, especially during commute times. This measure examines the proportion of person-miles of travel (PMT) in non-SOVs, which includes shared travel in general purpose lanes (GPLs), carpooling to make use of HOV requirements, as well as bus services running on a link, and rail service paralleling the link. This measure is quantified as shown in Equation 11.

$$\textit{Proportion of Non-SOV Travel} = \frac{PMT_{HOV} + PMT_{bus} + PMT_{rail}}{PMT_{total}} \qquad (11)$$

Where,

PMT_{HOV} = daily person-miles of travel in automobiles with occupancy of 2 or more in the study section;

PMT_{bus} = daily person-miles of travel on bus service in the study section;

PMT_{rail} = daily person-miles of travel on rail facilities running parallel to the study section; and

PMT_{total} = total daily person-miles of travel in the study section.

For transit services, such as bus and rail, the PMT is calculated for each link from the length, frequency of service, and average ridership details. In the case of HOV lanes, the PMT is estimated based on minimum-occupancy requirements. In addition to this, the average occupancy for automobiles is used to estimate the PMT in a non-SOV in the GPLs. For example, if average automobile occupancy in a region is 1.1, it would imply that every 100 vehicles traveling a section of roadway carried 110 persons on average. This implies that at a minimum, 20 persons rode with another person (which then qualifies as a non-SOV), and that 20 out of every 110 PMT (approximately 18 percent of total PMT) in the GPLs are in non-SOVs.

Extreme Values

For this measure, the best and worst possible values are defined as being equivalent to attaining specific GPL occupancy levels. Thus, the presence of higher-occupancy modes will make it easier to attain a higher equivalent GPL occupancy. The worst case scenario is assumed to be equivalent to having an overall occupancy of 1.14, and the best case equivalent to an overall occupancy of 1.63. These occupancies correspond to information from the most recent *National Household Travel Survey* (*37*) as the average occupancy levels for commute trips and general-purpose trips, respectively. These occupancy values correspond to proportions of non-SOV PMT of 25 percent and 77 percent, which are considered to be the worst and best case scenarios, respectively. It should be noted that there are locations where occupancy levels are well below 1.14. However, using lower worst-case occupancy values (1 is the theoretical minimum) can skew the comparison, by improving the value of the estimated measure for a majority of cases. Thus, a decision was made to consider any occupancy below 1.14 as the worst case scenario.

Daily NO_x, CO, and VOC Emissions in Grams per Mile

The emissions rate per equivalent ADT for NO_x, CO, and VOC are obtained from the MOBILE6 model. The MOBILE6 model provides emissions rates that vary by speed. The total daily emissions of each pollutant are estimated based on peak and off-peak speeds, and the proportion of the ADT occurring under peak and off-peak conditions. Equation 12 shows the daily emissions for each pollutant that are then aggregated into a single performance measure based on the relative damage costs for each.

$$\text{Daily } NO_x\text{, CO, and VOC emissions} = NO_x \times W_{NO_x} + CO \times W_{CO} + VOC \times W_{VOC} \quad (12)$$

Where,

NO_x = daily NO_x emissions in grams per mile of roadway;

CO = daily CO emissions in grams per mile of roadway;

VOC = daily VOC emissions in grams per mile of roadway; and

W_{NOx}, W_{CO}, W_{VOC} = weights (adding to 1) assigned to each pollutant based on their estimated damage costs.

The damage cost values are obtained from the *Highway Economic Requirements System* (*38*), and are shown in Table 10, along with the relative weights calculated based on these costs. Thus, the performance measure is obtained for individual links, and is aggregated as a length-weighted average to obtain the measure for the entire section. Figure 6 illustrates the process of calculating this performance measure. Appendix C shows the MOBILE6 emissions rates used in this analysis.

Table 10. Damage Costs for VOC, NO_x, and CO.

Pollutant	Damage Costs ($/ton)	Weight
VOC	2,750	0.42
NO_x	3,625	0.56
CO	100	0.02

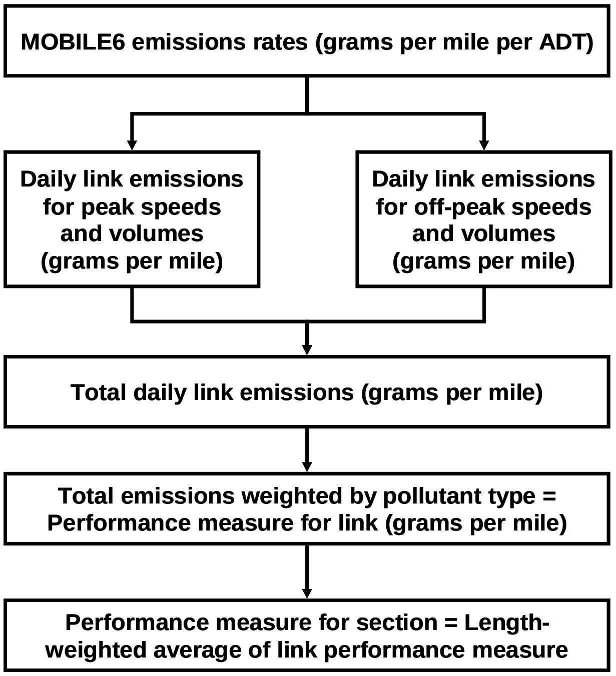

Figure 6. Estimation of Daily Combined VOC, NO$_x$, and CO Emissions.

Extreme Values

The extreme values for this measure are based on emissions for a range of ADT values, and different distributions of peak and off-peak conditions. The best case and worst case values for this measure are calculated to be 1.3 kilograms per mile and 181 kilograms per mile, respectively. Appendix C shows the process for calculating these extreme values.

Daily CO_2 Emissions in Grams per Mile

Total CO_2 emissions are calculated as a separate performance measure for individual links and for the entire study section. The calculation methodology is similar to the previous measure, and uses peak and off-peak speeds and volumes to estimate total emissions. The emissions rates used for the estimation of CO_2 were based on a study conducted by TTI, and are presented in Appendix C.

Extreme Values

Calculating extreme values for this measure is similar to the previous measure. The best and worst case emissions rates for CO_2 were calculated to be 3,000 kilograms per mile and 92,700 kilograms per mile, respectively.

Attainment of Ambient Air Quality Standards

This measure has different estimation procedures for the current and future situations, as discussed in the previous chapter. Equations 13 and 14, respectively, show the formula for estimating this measure for a current situation, and in the future.

$$\textit{Measure (Current) = Score (on scale of 0-1) based on non attainment level} \qquad (13)$$

$$\textit{Measure (Future) = Score for current scenario} + \frac{\Delta_{NOX,VOC}}{\Delta_{MAX-NOX,VOC}} \qquad (14)$$

Where,

$\Delta_{NOx,VOC}$ = Projected reduction in combined VOC and NO_x emissions from the current scenario; and

$\Delta_{MAX-NOx,VOC}$ = Maximum possible reduction in combined VOC and NO_x emissions from the current scenario (Estimation of this quantity is described in Appendix C).

Depending on the level of nonattainment (*39*), the performance measure for the current scenario can be estimated as shown in Table 11. The performance measure for the entire section is calculated as the length-weighted average of the measure for individual links.

Table 11. Performance Measure Values for Ozone Nonattainment.

Nonattainment Status	Performance Measure Value
In Attainment	1
Basic Deferred/Early Action Compact	0.8
Marginal Nonattainment	0.6
Moderate Nonattainment	0.4
Serious or Severe Nonattainment	0.2
Extreme Nonattainment	0

However, the nonattainment status for a region cannot be predicted with certainty in the future. To calculate the performance measure value for the future, the value for the current scenario is adjusted based on the reduction in emissions of ozone precursors (VOC and NO_x) relative to the maximum possible reduction in their combined emissions. The estimation of the maximum possible reduction in combined VOC and NO_x emissions is presented in Appendix C, and is estimated to be 165 kilograms per mile.

Extreme Values

This performance measure is expressed on a scale of 0-to-1 for the current scenario. For the future case, the measure values are also expressed on the same scale. For example, if an area that is currently in attainment further reduces NO_x and VOC emissions, the value of the performance measure remains 1. If an area currently in extreme nonattainment experiences a further increase in emissions, the measure value remains at 0. Thus, the best and worst case values for this measure are 1 and 0 respectively.

SCALING OF PERFORMANCE MEASURES

For each of the performance measures, a “scaled utility value” that represents the measure on a scale ranging from 0-to-1, must be obtained. These utility values are to be aggregated together as a weighted sum to obtain the overall sustainability evaluation result. The estimation of the best and worst case values (or scaling extremes) for each of the performance measures has been discussed in the previous section. Certain performance measures are already expressed as a percentage value, or on a 0-1 scale. In these cases, the measures themselves represent the scaled utility value.

For other performance measures, a utility function must be constructed for scaling. The utility function (or utility curve) expresses the variation in the scaled utility value for the range of values of the performance measure itself. So, for each performance measure, there are two points that are fixed on the utility curve - the first corresponding to the best possible value of the performance measure (which would be assigned a utility value =1) and the second corresponding to the worst possible value of the performance measure (which would be assigned a utility value =0) (See Figure 7).

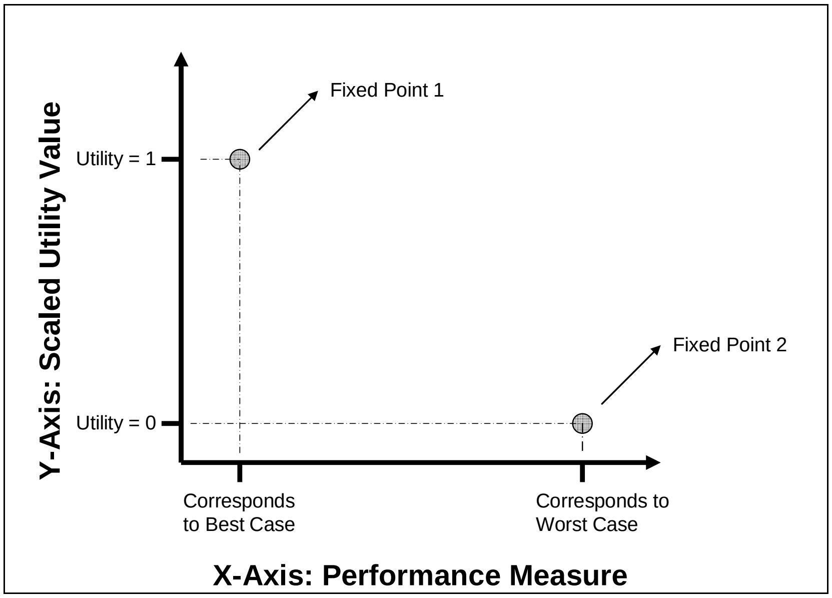

Figure 7. Fixed Points on the Utility Curve.

Therefore, the task of deriving a utility function involves fitting a curve through these two fixed points. The most commonly assumed and simple utility function is a straight line, which is referred to as “linear utility scaling”. If any other shape or functional form is assumed, the scaling is deemed to be "non-linear", as Figure 8 illustrates. Research findings have indicated that the use of linear or non-linear utility functions in an MAUT analysis is primarily a matter of the analyst's choice (*21*). However, there is an underlying assumption while using linear scaling. The assumption is that the value of improving a performance measure is the same no matter the initial value of the performance measure. But for certain measures, it can be intuitively judged that improving the performance when it is close to the worst case scenario is more valuable than a similar improvement occurring closer to the best case scenario. For performance measures that have a certain target, the utility curve may be s-shaped around that target, indicating an increased utility when the measure is close to the target.

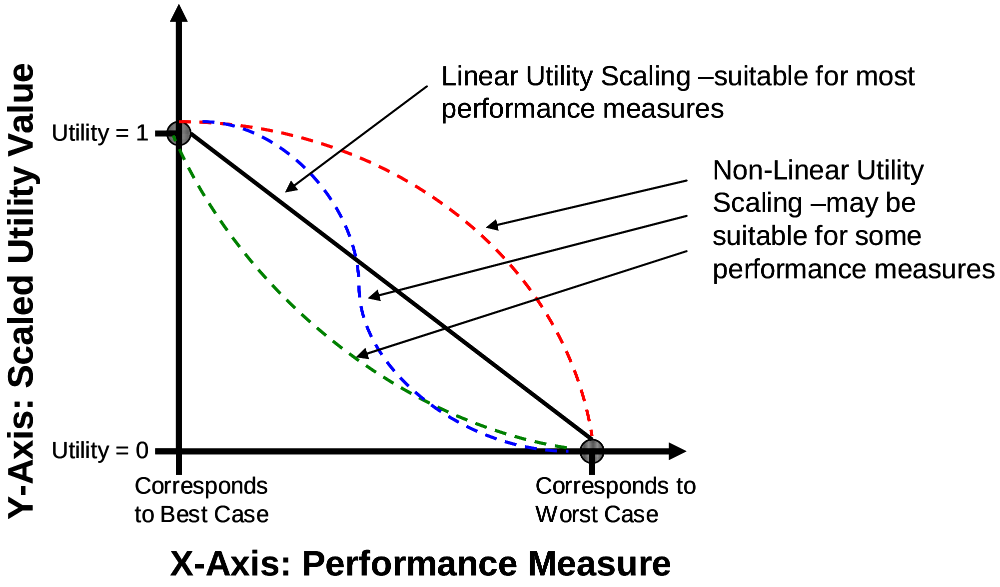

Figure 8. Illustration of Linear and Non-Linear Scaling for Performance Measures.

In this research, linear utility scaling was considered for a majority of the performance measures selected. However, a method for deriving non-linear utility functions is proposed, and was performed for two selected measures as an illustrative example. Table 12 summarizes the performance measures, their extreme values, and the type of utility scaling considered for each. The next section discusses the derivation of non-linear utility scaling for the performance measures selected for non-linear utility scaling.

Table 12. Details of Extreme Values and Utility Scaling for All Measures.

Reference Number	Performance Measure	Extreme Values		Type of Utility Scaling
		Best	Worst	
1a	Travel Time Index	1.00	1.50	Linear scaling of utilities
1b	Buffer Index	0.00	0.65	Linear scaling of utilities
2a	Annual severe crashes per mile	Depends on roadway type and number of lanes		Linear scaling of utilities
2b	Percentage lane miles under TMC surveillance	100%	0%	Measure represents utility value
3a	Land use balance	1.00	0.00	Measure represents utility value
3b	Truck Throughput Efficiency	170,704 daily truck miles/hour	5,640 daily truck miles/hour	Linear scaling of utilities
4a	Pavement condition score	100	0	Measure represents utility value
4b	Capacity addition within ROW	1.00	0.00	Measure represents utility value
4c	Cost recovery from alternate sources	1.00	0.00	Measure represents utility value
4d	Proportion of total person-miles of travel on non-SOVs	77%	25%	Non-linear scaling of utilities
5a	Daily NO_x, CO, and VOC emissions	1.28 kilograms per mile	180.5 kilograms per mile	Non-linear scaling of utilities
5b	Daily CO_2 emissions	2,993 kilograms per mile	92,702 kilograms per mile	Linear scaling of utilities
5c	Attainment of ambient air quality standards	1.00	0.00	Measure represents utility value

Non-Linear Utility Scaling

The issue of non-linear utility scaling was addressed in Zietsman et al.'s (*18*) study of sustainable performance measures, where different attributes were considered to have different shapes of utility function values, as Figure 9 (*18*) shows. These functions, while an improvement over assuming linearity, were defined based on mathematical properties of the function shapes. In this research, construction of the utility functions process provides a realistic representation of how the values of various performance measures are perceived to impact highway sustainability.

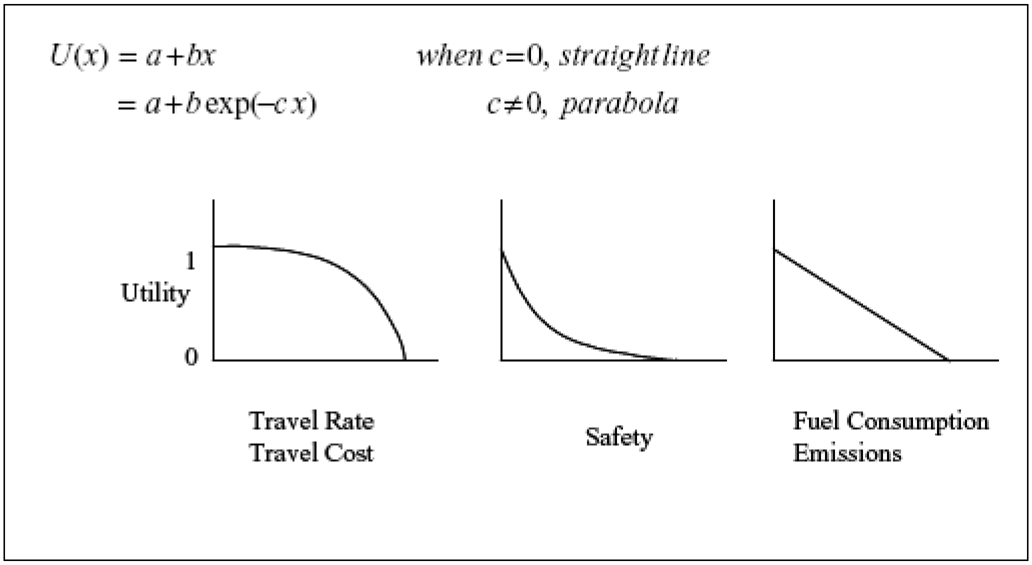

Figure 9. Examples of Utility Functions Used in Sustainability Assessments (*17*).

A decision-making technique known as AHP is used to derive non-linear utility functions for the two selected performance measures. As discussed in the literature review, the AHP is a process of eliciting the relative importance of different scenarios or quantities by making pair-wise comparisons between them. Based on the results of the comparisons made, an AHP matrix can be constructed from which the relative desirability, and consequently, data points on the utility curve can be obtained. The AHP decision-making process was performed through a guided workshop process for a group of transportation researchers and TxDOT personnel. Usually, an AHP procedure can either use a single set of responses obtained through consensus from the group of decision makers, or an average of the responses (*26*). For this process, the individual responses were collected from each decision maker, with a view of examining the trends and similarities between them, and later translated to a single set of responses to derive the utility function. The process of deriving the utility function is described in detail for the emissions measure, while only the results are presented for the measure concerning non-SOV travel.

Derivation of Utility Function for Daily NO_x, CO, and VOC Emissions

The quantification of this performance measure and the estimation of the scaling extremes (best/worst case) have been described in earlier sections. Based on this knowledge, two points on the utility curve can be fixed, as shown in Figure 10.

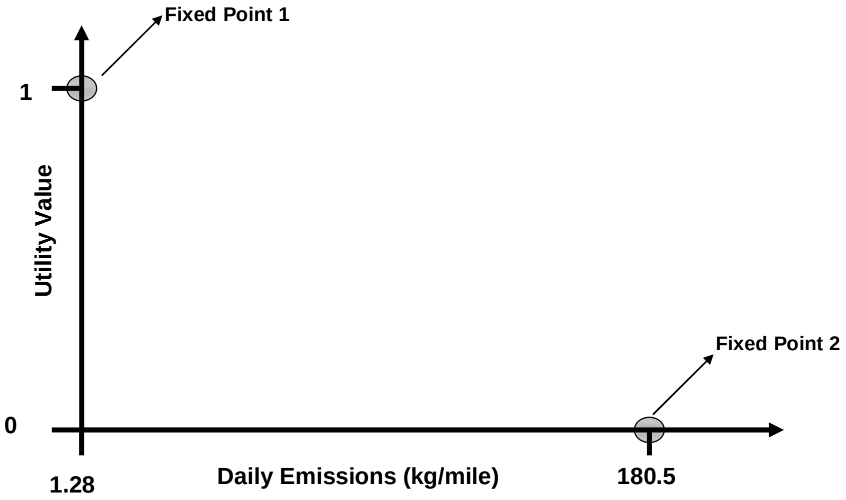

Figure 10. Fixed Points on Utility Curve for Emissions.

To derive a utility function between these two points, the range of values on the x-axis is split into four increments. The case of reducing emissions at each increment is termed as a scenario. For example, Scenario X could be defined as reducing daily emissions from 181 kg/mile-to-125 kg/mile, while Scenario Y could be defined as reducing emissions from 125 kg/mile-to-100 kg/mile. Based on knowledge of the performance measure and its variation, it is possible to compare the relative desirability or importance of the scenarios. This strength of preference is expressed on a numerical scale from 1-to-9, using a set of guidelines as devised by Saaty (*26*). A score of 1 implies that both scenarios are equally important, and a score of 9 implies that one scenario is absolutely more important than the other. Appendix D contains further details of conducting comparison process. Pair-wise comparisons are made for each pair of defined scenarios, and the results are used to populate an AHP matrix, from which utilities can be derived. The AHP matrix can also be used to check for consistency in a set of responses, and to rectify any inconsistencies in the decision-making process.

For the emissions measure discussed previously, four scenarios are defined covering the range of possible emissions levels between the best and worst case projections (see Figure 11).

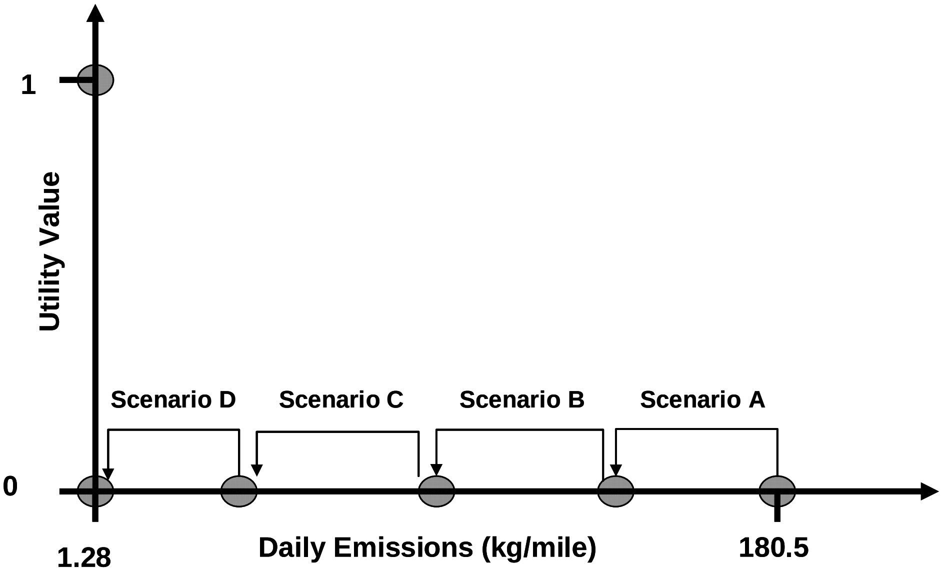

Figure 11. Scenarios Defined for the Emissions Performance Measure.

Table 13 provides the numerical details of each scenario. Verbal descriptors were used (ranging from “very bad,” “bad,” “moderate,” “good,” and “very good”) to describe the levels of attainment for each scenario. Decision makers were asked to perform a total of six pair-wise comparisons on the AHP scale, for all possible combinations of the scenarios. Based on the responses, an AHP matrix can be compiled and used to calculate points on the utility curve, and check for consistency.

Table 13. Evaluation Scenarios for Emissions Measure.

	Description of Improvement	
Scenario	**Daily Emissions**	**Verbal Descriptor**
A	180.50 kg/mile to 135.70 kg/mile	Very Bad to Bad
B	135.70 kg/mile to 90.89 kg/mile	Bad to Moderate
C	90.89 kg/mile to 46.09 kg/mile	Moderate to Good
D	46.09 kg/mile to 1.28 kg/mile	Good to Very Good

Rather than provide decision makers with scenarios relating to actual levels of the performance measurement, an alternative approach could have been to relate the performance measure (in this case, emissions) to the costs of impacts (such as health, environmental damage). However, the AHP process proposed is based on deriving the decision makers’ perception of how the value of a measure varies as the measure itself varies. Given this, it was felt that consideration of the measure itself rather than costs was preferable, as decision makers may tend to judge quantities expressed as costs as having a linear variation of utility.

Construction of AHP Matrix and Derivation of Utilities

The AHP matrix is a square matrix of order equal to the total number of options evaluated (in this case, four scenarios). The rows and columns represent each scenario, and each cell of the matrix represents the degree to which the row component dominates the column component on the AHP scale. If the column component is the dominant option, the reciprocal of the AHP scale score is entered as the cell value instead. The diagonal values of the AHP matrix are always unity, as each element is equally important when compared to itself (=1 on the AHP scale). Table 14 shows the AHP matrix used to derive the utility function, and is based on the responses from the six individual decision makers. Appendix D presents the AHP matrices for the individual decision makers and the utilities calculated for each.

Table 14. AHP Matrix for Deriving Utilities.

Scenario	**A**	**B**	**C**	**D**
A	1.00	5.00	7.00	9.00
B	0.20	1.00	5.00	7.00
C	0.14	0.14	1.00	3.00
D	0.11	0.20	0.14	1.00

For this matrix, the normalized Eigen vector represents the relative desirability of the different scenarios (each of which represents a specific increment in the performance measure value). Thus, utilities of various points on the curve can be determined, from which a utility function can be derived. Table 15 shows the calculated utilities and Table 16 shows the resulting points on the utility curve. Figure 12 shows the shape of the utility curve derived.

Table 15. Normalized Eigen Vector for Relative Priorities.

Scenario	**Relative Priority (Eigen Vector)**	**Cumulative Priority (Utility Curve)**
A	0.64	0.64
B	0.25	0.88
C	0.08	0.97
D	0.04	1.00

Table 16. Points on Utility Curve.

Measure Value	Utility
180.50 kg/mile	0.00
135.70 kg/mile	0.64
90.89 kg/mile	0.89
46.09 kg/mile	0.96
1.28 kg/mile	1.00

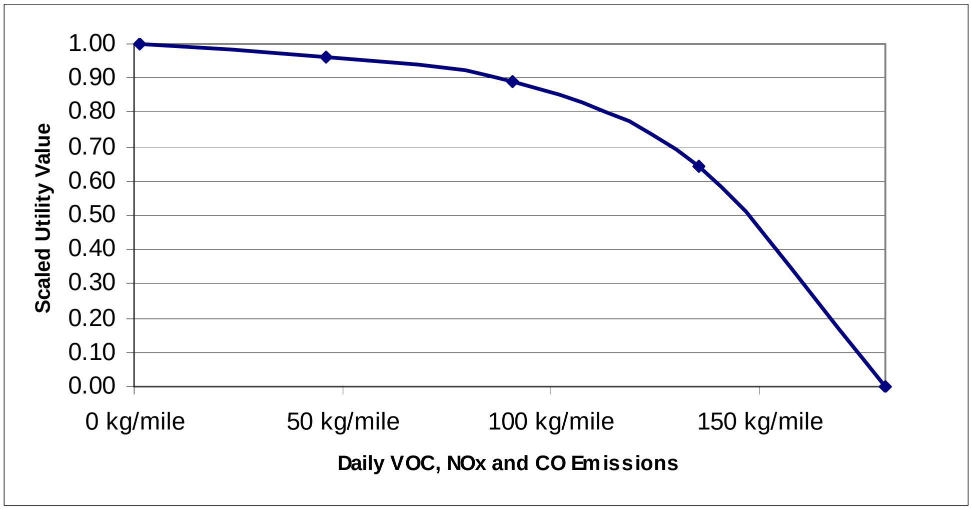

Figure 12. Utility Curve Plotted from Results of AHP Evaluation.

Checking for Consistency

The consistency of responses obtained from the AHP can be checked by calculating the Consistency Index (CI), and Consistency Ratio (CR), as shown in Equations 15 and 16 respectively. Generally, CR values below 0.1 indicate a good degree of consistency in the pair-wise comparisons. The CI and CR values for this measure are 0.09 and 0.1 respectively, which are found to be satisfactory.

$$CI = (\lambda_{max}-n)/(n-1) \qquad (15)$$

$$CR = CI/RI \qquad (16)$$

Where,

n = order of matrix;

λ_{max}= principal eigenvalue of AHP matrix; and

RI = random index –0.9 for matrix of order 4.

Deriving Equation for Utility Function Based on AHP Results

Based on the data points obtained from the AHP, a utility function is derived using a method of least squares-estimation (see Equation 17).

$$y = 1.019 - 0.018e^{0.022x} \tag{17}$$

Where,

y = scaled utility value; and,

x = combined VOC, NO_x and CO emissions, in kg/mile.

Derivation of Utility Function for Proportion of Non-SOV Travel

The utility function for the measure estimating proportion of non-SOV travel is derived using the same technique as for the previous measure. Tables 17 and 18 show the AHP matrix and the derived points on the utility curve. The CI and CR values are 0.066 and 0.073, respectively, indicating a fairly high level of consistency. Figure 13 shows the utility curve for this measure.

Table 17. AHP Matrix for Deriving Utilities.

Scenario	A	B	C	D
A	1.00	3.00	5.00	5.00
B	0.33	1.00	3.00	5.00
C	0.20	0.33	1.00	3.00
D	0.20	0.20	0.33	1.00

Table 18. Points on Utility Curve.

Measure Value	Utility
25.00%	0.00
38.00%	0.54
51.00%	0.81
64.00%	0.94
77.00%	1.00

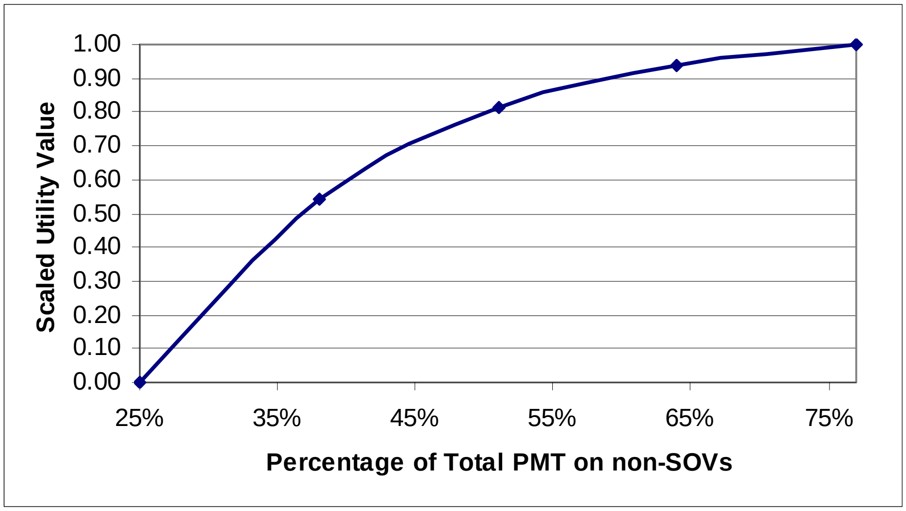

Figure 13. Utility Curve Based on Results of AHP Evaluation.

Equation 18 shows the utility function derived for this performance measure. Appendix D contains the detailed calculations and derivation of the final utility function.

$$y = 1.059 - 4.249e^{-5.558x} \tag{18}$$

Where,

y = scaled utility value; and

x = percentage of total person-miles of travel that is in a non-SOV.

Summary of the Utility Scaling Process

The process of scaling of various performance measures was discussed in this section. Some of the performance measures (expressed as a percentage, or on a 0-to-1 scale) already reflected their scaled utility values. For other measures, linear utility scaling was considered for the majority, while a methodology for deriving non-linear utility scaling was proposed, and demonstrated for two selected measures. Thus, each of the performance measures used in this research can be scaled appropriately, and used for further analysis.

WEIGHTING AND AGGREGATING SCALED MEASURES

While applying the MAUT to a set of performance measures, an aggregate indicator value is obtained as the weighted sum of the individually scaled measures. This results in a composite indicator that is also expressed on the same scale, in this case, from 0-to-1. The weights for individual measures are allocated such that they add to 1, with the measures that are deemed more important by the decision makers being given a higher weight.

In this thesis, the process of derivation of weights is not dealt with in detail. The weights were obtained through a group decision-making process with stakeholders. Two sets of weights are used – termed as goal-weights and measure-weights. Because the strategic plan has five goals, each addressed by a set of performance measures, the performance measures corresponding to each goal were first assigned individual weights (termed as measure-weights). This enables calculation of goal-wise performance – to evaluate which goals are being sufficiently addressed from a sustainability perspective and which require further improvement. The set of goal-weights then define the relative importance assigned to TxDOT's five goals – the aggregate indicators for each goal can be combined into a final sustainability evaluation index. Figure 14 illustrates this process. Table 19 shows the weights used for this analysis.

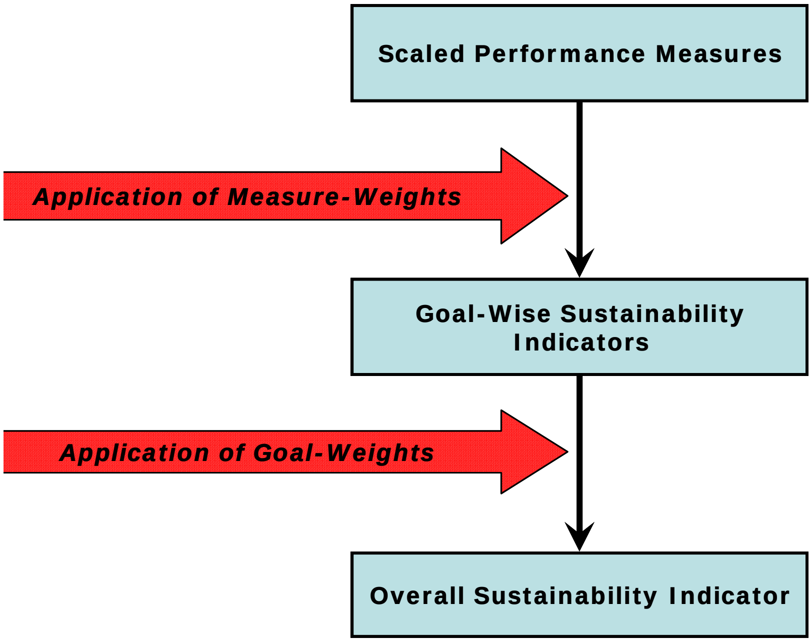

Figure 14. Application of Weights to Aggregate-Scaled Performance Measures.

Table 19. Goal Weights and Measure Weights for MAUT Analysis.

Goal	Goal-Weight	Performance Measure	Measure-Weight
Reduce Congestion	25 %	Travel Time Index	60%
		Buffer Index	40%
Enhance Safety	30%	Annual severe crashes per mile	80%
		Percentage lane miles under traffic monitoring/surveillance	20%
Expand Economic Opportunity	10%	Land use balance	50%
		Truck throughput efficiency	50%
Increase Value of Transportation Assets	10%	Average pavement condition score	20%
		Capacity addition within available ROW	20%
		Cost recovery from alternative sources	40%
		Proportion of non single-occupant travel	20%
Improve Air Quality	25%	Daily NO_x, CO, and VOC emissions per mile of roadway	75%
		Daily CO_2 emissions per mile of roadway	15%
		Attainment of ambient air quality standards	10%

CONCLUDING REMARKS

This chapter covered the techniques used to apply the MAUT for sustainability evaluation of a given highway section – including the process of quantification, scaling, and aggregation of the performance measures. The following chapters describe the application of this methodology for a case study, and the results and conclusions drawn from the process.

CHAPTER V

APPLICATION OF METHODOLOGY – CASE STUDY FOR US 281

DESCRIPTION OF STUDY SECTION

A 15-mile section of US 281 highway, in San Antonio, Texas was chosen as the study corridor. The sustainability evaluation based on the developed model was performed for this highway. Figure 15 shows a map of the study section.

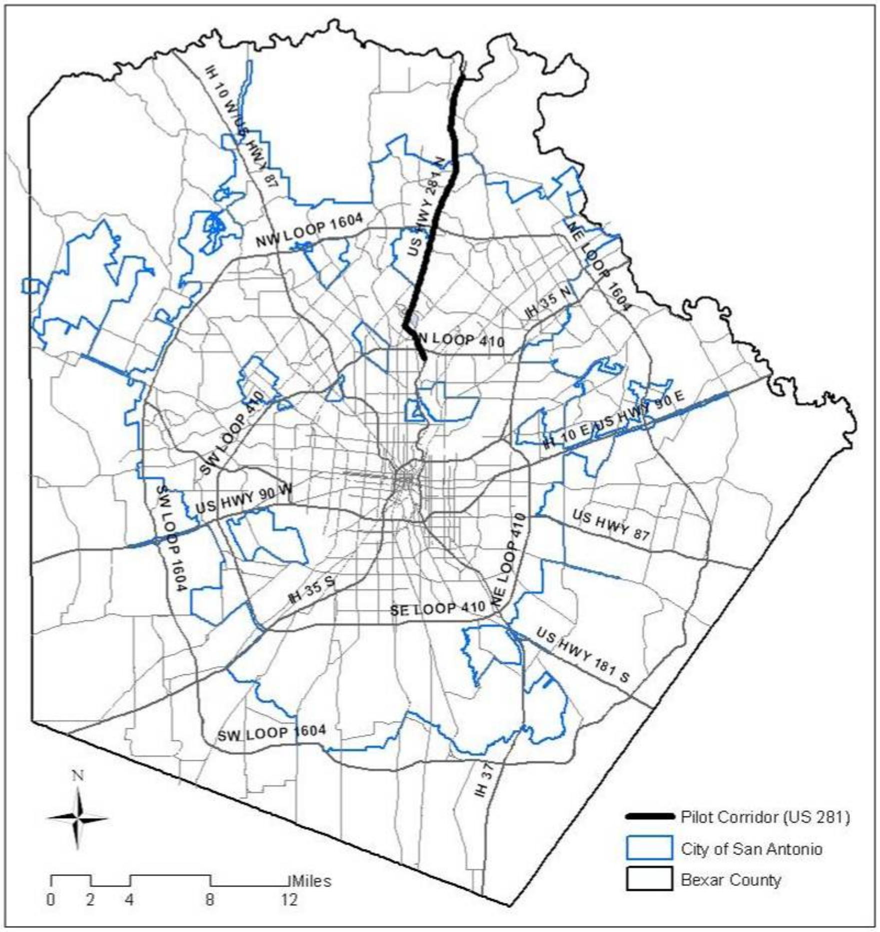

Figure 15. Location of Study Corridor.

The study location on US 281 stretches from I-410 in downtown San Antonio in the south, to the Comal/Bexar county line in the north. The section from I-410 to Loop 1604 (a distance of approximately seven miles) is fully access controlled, comprised of three lanes per direction with a concrete barrier in the median. The remaining section from Loop 1604 to the Comal/Bexar county line is a divided facility with limited at-grade access, having three lanes per direction for two miles, and two lanes per direction beyond that point. The corridor begins next to the San Antonio International Airport with predominately dense commercial development. Past Loop 1604, the development becomes less dense, with pockets of commercial development (mainly retail). Closer to the Bexar/Comal county line, the development becomes sparser with occasional lower density residential developments and small retail outlets. Figures 16 and 17 illustrate how the character of the study section changes further away from downtown San Antonio.

Figure 16. Study Section Close to Downtown San Antonio.

Figure 17. Study Section Close to Bexar/Comal County Line.

BASIC ANALYSIS COMPONENTS

Identification of Links

The selected study section of US 281 is subdivided into four links for the analysis. Table 20 shows the beginning points and ending points of each link, and the link lengths. The links were selected to begin and end at major crossing roadways, and to be homogenous in terms of geometric characteristics, traffic characteristics, and the overall nature of the surrounding area.

Table 20. Link Details and Lengths.

Link	Start	End	Length (miles)
1	I-410 N	Bitters Road	3.9
2	Bitters Road	Evans Road	5.2
3	Evans Road	Bulverde Road	4.0
4	Bulverde Road	Comal County Line	1.9
Total Section	I-410 N	Comal County Line	14.9

Identification of Evaluation Scenarios

For this research, two evaluation scenarios are considered – one representing current conditions for the study section and another representing future conditions. These are referred to as the "base case" and "future case" scenarios, respectively. The base case is set at the year 2005, while the future case is the year 2025. The data elements required for evaluating each performance measure are assembled relevant to these two years, and the analysis performed. In the future case scenario, for data elements not known with certainty, suitable assumptions are made based on the relevant transportation planning initiatives in the regions, and outputs from the travel demand model.

Data Elements

The most important data element required for this analysis is traffic volumes, which are used in the evaluation of travel times (for crash prediction) and calculation of emissions. Table 21 shows the traffic volumes for the study section that were obtained from the regional travel demand model for the base case and future case scenarios.

Table 21. Traffic Volumes for Base Case and Future Case Scenarios.

Link	Length (miles)	Daily Volume-2005	Number of lanes- 2005	Daily Volume-2025	Number of lanes -2025
1	3.89	101,364	6	156,129	6
2	5.22	77,314	6	169,629	6
3	3.97	36,884	4	102,067	6
4	1.85	33,887	4	75,261	6

The other data elements used in this analysis include pavement conditions, truck percentages, transit options, details on project costs and recovery, surveillance through traffic monitoring centers, land use, availability of ROW, and miscellaneous details. These individual items are discussed, where relevant, for individual performance measures. The following section covers calculating and scaling the individual performance measures for the study section, and their aggregation into a composite sustainability indicator.

CALCULATION AND SCALING OF INDIVIDUAL MEASURES

Travel Time Index

Speed estimation procedures are used to calculate the peak travel speeds for individual links and the estimates are used to derive the peak travel times. Tables 22 and 23 show the calculated and scaled performance measures for the base case and future case, respectively.

Table 22. Travel Time Index for Base Case Scenario.

Link	Travel Time for Posted Speed Limit (mins)	Travel Time for Peak Conditions (mins)	Travel Time Index	Scaled Measure
1	3.89	4.26	1.09	0.81
2	4.82	4.82	1.00	1.00
3	3.66	3.66	1.00	1.00
4	1.71	1.71	1.00	1.00
Total Section			1.04	0.92

Table 23. Travel Time Index for Future Case Scenario.

Link	Travel Time for Posted Speed Limit (mins)	Travel Time for Peak Conditions (mins)	Travel Time Index	Scaled Measure
1	3.89	6.14	1.58	0.00
2	4.82	8.95	1.86	0.00
3	3.66	4.36	1.19	0.62
4	1.71	1.85	1.08	0.83
Total Section			1.52	0.00

The tables show that the Travel Time Index values are much higher for the future case scenario, which is expected owing to the higher traffic volumes. Also, for the base case scenario, the Travel Time Index values obtained from the speed curves indicates uncongested travel for links 2, 3 and 4. If real travel time data were to be used, the calculated travel time indices would be slightly higher. This difference is due to the macroscopic nature of the speed estimation model. However, the speed estimation is preferred over measuring travel times, as it provides a common methodology for the base case and future case scenarios, allowing for comparison of the results.

Buffer Index

The Buffer Index is calculated based on the relationship with the Travel Time Index. Table 24 shows the calculated Buffer Index values and the scaled performance measures. Similar to the Travel Time Index, the Buffer Index is also higher for the future case scenario, indicating decreased reliability of travel.

Table 24. Measured Values and Scaled Values for Buffer Index.

Link	Base Case		Future Case	
	Buffer Index	**Scaled Value**	**Buffer Index**	**Scaled Value**
1	0.19	0.71	0.64	0.01
2	0.00	1.00	0.64	0.01
3	0.00	1.00	0.35	0.46
4	0.00	1.00	0.17	0.74
Total Section	0.08	0.88	0.51	0.21

Annual Severe Crashes per Mile

The analysis of crashes is based on the roadway type. For the base case scenario, Links 3 and 4 (Evans Road to Comal County Line) were evaluated as rural highways, while Links 1 and 2 were evaluated as freeways. Links 3 and 4 represent the portions that currently have at-grade access and lower traffic volumes. For the future case scenario, the travel demand model outputs show increased volumes by considering an increased number of lanes for Links 3 and 4. Additionally, regional transportation plans have indicated that the entire section of US 281 to the Comal County line will be upgraded to expressway standards in the future. Thus, in the future case scenario, all links are assumed as freeways. Table 25 shows the performance measures and the scaled values.

Table 25. Measure Values and Scaled Values for Annual Severe Crashes.

Link	Base Case		Future Case	
	Annual Severe Crashes per Mile	Scaled Measure	Annual Severe Crashes per Mile	Scaled Measure
1	13.32	0.42	20.52	0.11
2	10.16	0.56	22.29	0.03
3	11.31	0.00	13.41	0.42
4	7.80	0.00	9.89	0.57
Total Section	10.99	0.30	17.93	0.22

The results show that safety performance is improved in the future, despite increased traffic volumes in the study section. This is mainly due to the increased number of lanes on Links 3 and 4. It can be seen that for links 3 and 4, despite an increase in overall crashes, the scaled measure values are improved. This is because the scaling extremes are based on the number of lanes, and links 3 and 4 have an increased number of lanes in the future scenario, resulting in higher number of crashes for the corresponding worst case.

Percentage Lane Miles under TMC Surveillance

The TMC monitoring program in San Antonio, TransGuide, currently covers US 281 only south of the study section. However, the ultimate coverage area for TransGuide extends to the north of Loop 1604 on US 281 (corresponding to Links 1 and 2). Thus, for evaluating this performance measure, no TMC surveillance was considered for the base case scenario, and surveillance was considered as present for Links 1 and 2 in the future case scenario. Table 26 shows the tabulated and scaled measure values.

Table 26. Percentage Lane-Miles under TMC Surveillance.

Link	Base Case		Future Case	
	Measure Value	Scaled Value	Measure Value	Scaled Value
1	0.00	0.00	100.00	1.00
2	0.00	0.00	100.00	1.00
3	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00
Total Section	0.00	0.00	61.02	0.61

Land Use Balance

The input details for the base case are obtained from parcel-based GIS data of current land use. In this data, certain unoccupied land areas are classified as “developable”, and sub-classified as “commercial” or “residential”. In the base case, this land is classified as “Institutional/Public”, and in the absence of a future land use plan, it is assumed that all of this land is occupied by the designated use in the future scenario (i.e., it becomes fully developed as per the land use plan). Thus, the land use shifts to a greater proportion of commercial and residential uses. Tables 27 and 28, respectively, show the land use details and calculated measures for the base case and future case scenarios. In this case, the calculated performance measure also represents the scaled value.

Table 27. Land Use Balance for Base Case Scenario.

Link	Area in Half-Mile to either side (sq. miles)			Land Use Balance
	Residential	Commercial/ Industrial	Institutional/ Public	
1	0.68	2.23	0.50	0.80
2	2.41	1.37	0.66	0.89
3	1.63	1.10	1.00	0.98
4	0.75	0.09	0.95	0.78
Total Section	5.48	4.80	3.11	0.98

Table 28. Land Use Balance for Future Case Scenario.

Link	Area in Half-Mile to either side (sq. miles)			Land Use Balance
	Residential	Commercial/ Industrial	Institutional/ Public	
1	0.69	2.27	0.45	0.78
2	2.49	1.71	0.25	0.78
3	1.81	1.65	0.27	0.82
4	0.79	0.19	0.81	0.87
Total Section	5.79	5.83	1.78	0.90

Truck Throughput Efficiency

The percentage trucks for the base case scenario were obtained from TxDOT's Road-Highway Inventory and Network (RHiNo) for each of the links. For the future case scenario, an unchanged percentage of trucks were considered. However, the changed volumes and operational speeds would impact the final performance measure, even when an unchanged truck percentage is considered. Tables 29 and 30 show the calculated and scaled performance measures.

Table 29. Truck Throughput Efficiency for Base Case Scenario.

Link	Proportion of Trucks (%)	Truck Volumes per Lane (veh./lane/day)	Truck Operating Speed (mph)	Truck Throughput Efficiency	Scaled Measure
1	6.88	1163	51.51	59,879	0.33
2	5.20	670	61.10	40,940	0.21
3	4.27	394	61.10	24,075	0.11
4	3.70	313	61.10	19,152	0.08
Total Section				39,894	0.21

Table 30. Truck Throughput Efficiency for Future Case Scenario.

Link	Proportion of Trucks (%)	Truck Volumes per Lane (veh./lane/day)	Truck Operating Speed (mph)	Truck Throughput Efficiency	Scaled Measure
1	6.88	1791	35.73	63,975	0.35
2	5.20	1470	32.90	48,367	0.26
3	4.27	727	51.41	37,369	0.19
4	3.70	464	56.40	26,176	0.12
Total Section				51,064	0.28

The tables show that the measure improves only slightly in the future case scenario. This indicates that from an economic development perspective, the number of trucks on the section can be increased without adversely affecting the highway system.

Pavement Condition Score

The pavement condition score for the current conditions were obtained from TxDOT's PMIS database. For the future case scenario, a uniformly improved pavement condition (with a score of 95) was assumed. This assumption was made based on the fact that a capacity expansion project was included in the future case, which would indicate an overall improvement in pavement quality. Table 31 shows the performance measures and scaled values for the base case and future case scenarios.

Table 31. Pavement Condition Score.

	Base Case		Future Case	
Link	Measure Value	Scaled Value	Measure Value	Scaled Value
1	89	0.89	95	0.95
2	77	0.77	95	0.95
3	100	1.00	95	0.95
4	100	1.00	95	0.95
Total Section	89	0.89	95	0.95

Capacity Addition within ROW

Capacity addition within the available ROW is not possible for Links 1 and 2 (which have a raised barrier median and fairly dense development along the roadway). Links 3 and 4, however, have adequate median width for capacity addition. For the future case scenario, it is assumed that some of this area is used for added capacity, thereby reducing the available area in the future. It can be noted that in this analysis, the trade-off between safety performance and loss of median width would be reflected by the respective performance measures if the crash estimation makes use of the accident modification factor for median width (discussed in further detail in Appendix A). Table 32 shows the possible lane additions and the calculated performance measure values for the base case and future case scenarios. In this case, the performance measure value also represents the scaled measure.

Table 32. Capacity Addition within Available ROW.

Link	Number of Lanes that can be added within available ROW		Performance Measure Value	
	Base Case	Future Case	Base Case	Future Case
1	0	0	0	0
2	0	0	0	0
3	3	1	0.75	0.25
4	4	2	1	0.5
Total Section			0.32	0.13

Cost Recovery from Alternate Sources

The roadway is currently a free roadway operated by TxDOT. There are future plans to expand the section of the road beyond Loop 1604 and operate it as a toll road. The project cost is estimated at $300 million, of which over $100 million is to be contributed by the local Metropolitan Planning Organization (MPO). Significant toll revenue is expected to be generated from this project (*40*). Based on these details, the measure is estimated for the base case and future case scenarios. The following table shows that the measure improves in the future owing to recovery of expenses through tolling for Links 3 and 4. Table 33 shows the measure values for the base case and future case scenarios. The estimation of this performance measure results in a recovery factor value (a proportion of costs) that is on a 0 to 1 scale. Thus, the measure can be estimated for the entire section as the length-weighted average of the individual link values, even if the actual costs incurred are significantly different for different links.

Table 33. Cost Recovery from Alternate Sources.

Link	Base Case			Future Case		
	Proportion of Capital Covered	Proportion of O&M Covered	Measure Value	Proportion of Capital Covered	Proportion of O&M Covered	Measure Value
1	0	0	0.00	0	0	0.00
2	0	0	0.00	0	0	0.00
3	0	0	0.00	0.25	1	0.7
4	0	0	0.00	0.25	1	0.7
Total Section			0.00			0.27

Proportion of Total Person-Miles of Travel in Non-SOVs

Currently, the San Antonio metropolitan transportation agency (VIA Transit) provides a regular bus service on Links 1 and 2 of the study section. The route runs from approximately 5:45 am to 8:30 pm, with a daily frequency of approximately 30 buses (the average occupancy assumed for each bus is obtained from the 2005 National Transit Database statistics for VIA Transit. It is calculated as the ratio of total passenger miles traveled to total vehicle revenue miles for the agency, which approximately equals 9.5). For the future case scenario, an extended bus service for all links is considered, with the same frequency of service. Rail facilities are not considered in either scenario. For both scenarios, general-purpose lane occupancy of 1.25 is considered to calculate person-miles of non-SOV travel. Tables 34 and 35, respectively, show the calculated measure and scaled values for the base case and future case scenarios. The scaling is done based on the non-linear utility curve derived. It can be seen that the transit service provides an almost negligible contribution to the total person-miles of travel in the study compared to non-SOV auto travel, as indicated by the fact that the measure does not vary much from link to link, or from the base and the future.

Table 34. Proportion of Non-SOV Travel - Base Case Scenario.

Link	Total Daily SOV PMT	Total Daily Non-SOV PMT	Proportion of PMT by Non-SOV	Scaled Measure
1	295,730	198262	40.1%	0.60
2	302,685	203278	40.2%	0.60
3	109,823	73216	40.0%	0.60
4	47,018	31345	40.0%	0.60
Total Section	755,256	506100	40.1%	0.60

Table 35. Proportion of Non-SOV Travel - Future Case Scenario.

Link	Total Daily SOV PMT	Total Daily Non-SOV PMT	Proportion of PMT by Non-SOV	Scaled Measure
1	455,505	304779	40.1%	0.60
2	664,099	444220	40.1%	0.60
3	303,905	203735	40.1%	0.60
4	104,424	70143	40.2%	0.60
Total Section	1,527,934	1022878	40.1%	0.60

Daily NO_x, CO, and VOC Emissions

The emissions are calculated based on emissions rates obtained from MOBILE6, peak and off-peak traffic speeds, and the split of traffic between peak and off-peak times.

The emissions for each of the pollutants is combined based on their damage costs to obtain a composite measure. For the base case scenario, it is assumed that 35 percent of the traffic occurs during peak conditions (this data is obtained from analysis of hourly traffic counts along the corridor), while for the future case scenario, 50 percent of the traffic occurs during peak conditions (owing to increased congestion). Tables 36 and 37 show the calculated measure values and the scaled measure values. The scaling for this measure is also done based on the non-linear utility function derived in the previous chapter.

Table 36. VOC, NO_x, and CO Emissions for the Base Case Scenario.

Link	**Total Daily Emissions (grams/mile)**			**Combined Emissions (grams/ mile)**	**Scaled Measure**
	VOC	**NO_x**	**CO**		
	Relative Weight				
	0.42	**0.56**	**0.02**		
1	26,802	192,204	805,097	131,422	0.68
2	18,545	176,126	678,235	116,954	0.77
3	8,847	84,024	323,566	55,796	0.96
4	8,128	77,196	297,270	51,261	0.96
Total Section	16,827	143,566	569,774	96,321	0.86

Table 37. VOC, NOx, and CO Emissions for the Future Case Scenario.

Link	**Total Daily Emissions (grams/mile)**			**Combined Emissions (grams/ mile)**	**Scaled Measure**
	VOC	**NOx**	**CO**		
	Relative Weight				
	0.42	**0.56**	**0.02**		
1	20,027	43,118	571,937	41,478	0.97
2	21,483	48,919	642,904	46,440	0.97
3	11,227	30,414	419,367	28,272	0.98
4	8,038	22,919	317,706	21,152	0.99
Total Section	16,710	39,265	524,678	37,183	0.98

The tables show that the future case scenario is better than the base case scenario, despite the increases in traffic volumes. This can be explained by the reduced emissions rates for the future considered by emissions models such as MOBILE6, which reflect the technological improvements that reduce vehicular emissions.

Daily CO_2 Emissions

Calculating this measure is similar to the previous measure, and is based on vehicle speeds and the corresponding emissions rate. Table 38 shows the calculated and scaled performance measures for base case and future case scenarios.

Table 38. Daily CO_2 Emissions.

	Base Case		Future Case	
Link	Daily CO_2 Emissions (grams/mile)	Scaled Value	Daily CO_2 Emissions (grams/mile)	Scaled Value
1	55,079,712	0.28	91,939,355	0.00
2	42,592,459	0.45	100,788,967	0.00
3	20,319,647	0.76	56,138,127	0.26
4	18,668,248	0.78	41,039,841	0.47
Total Section	36,959,007	0.53	79,206,602	0.00

Unlike the VOC, CO, and NO_x emissions measure, this measure performs significantly worse in the future case scenario. This is explained by the fact that unlike other emissions, CO_2 emissions remain at the same rate in the future (rates are not expected to be considerably reduced through technological advancements), and therefore increase as total traffic increases.

Attainment of Ambient Air Quality Standards

All links of the study section are located in Bexar County, Texas. In 2005, this region was classified as “Basic/Deferred” with respect to nonattainment of eight-hour ozone standards, though subsequently (at the end of 2007) the region has been moved into attainment status. For the purpose of this study, the status as of 2005 is considered.

Table 39 shows the calculated performance measure for base case and future case scenarios. In this case, the measure value represents the scaled measure itself.

The table shows that the measure value improves in the future case scenario, indicating progress toward the air quality attainment. This is due to the reduction in emissions rates for ozone precursors, and is reflected in the recent reassignment of Bexar County to an ozone standards attainment region.

Table 39. Attainment of Ambient Air Quality Standards.

Link	Current Measure Value	Reduction in Daily Ozone Precursor Emissions in Future (grams/mile)	Maximum Possible Daily Reduction (grams/mile)	Relative Reduction in Emissions	Future Measure Value
1	0.8	87,697	165,963	0.53	1.00
2	0.8	71,066	165,963	0.43	1.00
3	0.8	29,458	165,963	0.18	0.97
4	0.8	30,902	165,963	0.19	0.98
Total Section	0.8	-	-	-	0.99

COMBINED RESULTS OF SUSTAINABLITY EVALUATION

The individual scaled performance measures (each expressed on a 0-to-1 scale) are combined as weighted sums to obtain overall sustainability evaluation results. To obtain goal-wise performance, the measure-weights are applied to individual measures within each goal. The goal-wise index values are then combined based on the goal weights to obtain an overall sustainability evaluation.

Table 40 shows the results of the goal-wise evaluation for the entire section and the results are shown graphically in Figure 18. The table shows that the performance on the safety goal and air quality goal improves, while goal 3 (expand economic opportunity) remains almost unchanged. The most significant reduction in performance is with respect to congestion – indicating that steps need to be taken toward congestion mitigation.

Table 40. Goal-Wise Sustainability Indicators for Entire Study Section.

Goal	Reduce Congestion	Enhance Safety	Expand Economic Opportunity	Increase Value of Transportation Assets	Improve Air Quality	All Goals Combined
Base Case	0.91	0.24	0.59	0.37	0.81	0.60
Future Case	0.08	0.30	0.59	0.34	0.83	0.41
Percentage Change	-90.74%	22.34%	-0.42%	-7.66%	3.15%	-31.12%

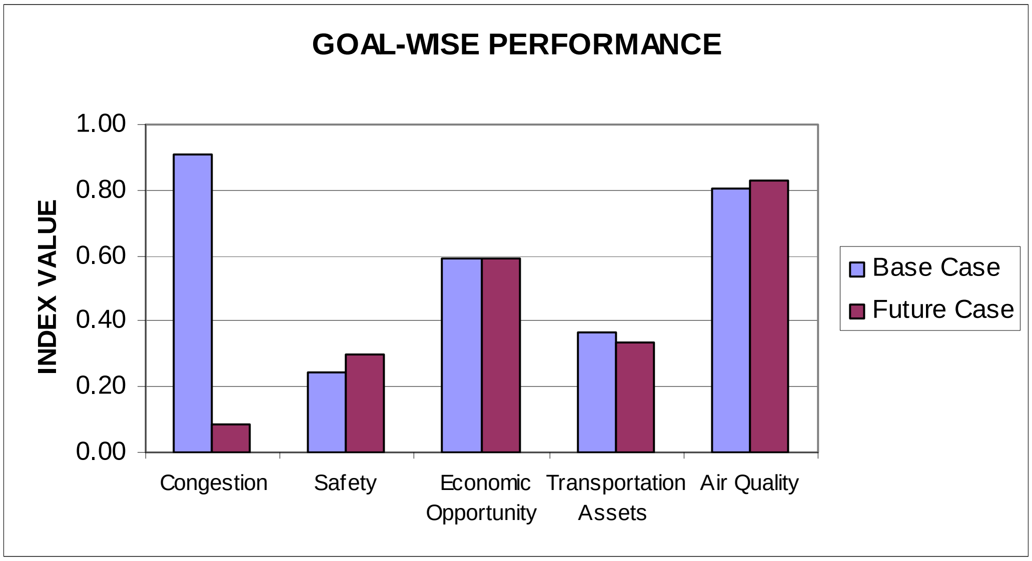

Figure 18. Graphical Representation of Goal-Wise Performance for Entire Study Section.

Goal weights and measure weights can also be applied to the scaled measures for individual links to assess performance by link. Table 41 shows the overall sustainability indicator values for the base and future cases for individual links. Figure 19 shows this performance graphically. The results show that while there is a reduction in the overall sustainability indicator value for the future case scenario when compared to the base case scenario for the first three links, the extent of the reduction is larger for the links closer to downtown San Antonio. While these represent links that are the most congested, and have the highest volumes, the fact that they are located closer to the city center makes it easier to address the issue of sustainability by providing better alternate transportation facilities. The final link has a marginally better sustainability indicator value for the future scenario, than for the current. This is possibly due to lower traffic volumes affecting the economic-related measures in the base case. Also, the increase in volumes in the future may not have been to an extent that adversely impacts safety, congestion, or environmental factors.

Table 41. Link-Wise Sustainability Indicator Values.

Link	Base Case	Future Case
1	0.54	0.38
2	0.65	0.36
3	0.58	0.55
4	0.57	0.65
Total Section	0.60	0.41

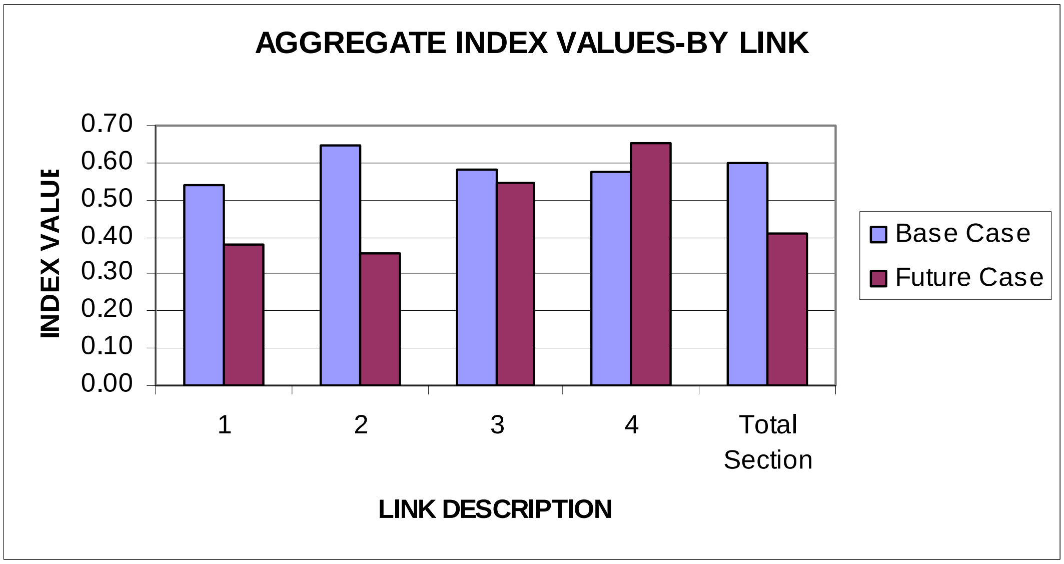

Figure 19. Graphical Representation of Link-Wise Sustainability Evaluation Results.

DISCUSSION OF RESULTS

The sustainability evaluation methodology was applied to the selected section of US 281, in San Antonio, Texas. From a sustainability perspective, the most damaging aspect in the future case scenario is due to the increase in traffic volumes that affect congestion, safety, and greenhouse gas emissions. However, there is some mitigation of these impacts due to technological advancements that reduce toxic emissions and due to the expansion of ITS facilities. Addition of more transit facilities, leveraging of alternate funding, and the importance of asset management are also highlighted in the results. For the case study corridor, links that performed worse than average are identified. Goal-wise progress was assessed to see which goals were not being met, and help identify how to achieve them in a sustainable manner.

This methodology is widely applicable and can be used to compare the sustainability of different highways, or of different planning scenarios for a particular highway. It assists in reinforcing what is common knowledge, in that it indicates the impact increased traffic has on sustainability of a highway. But, by examining a set of indicators and providing a detailed analysis of goal-wise and link-wise performance, steps to maximize the progress toward sustainability can be identified. The steps involved in the analysis provide a logical and scientific method of translating concerns about sustainability into a measurable indicator of progress on the basis of a set of goals, objectives, and performance measures.

Another aspect to be considered here is that this methodology is not the whole solution for a transportation agency to achieve goals of sustainability. The most significant progress can be achieved when sustainability is incorporated into the goals themselves. However, for reasons discussed earlier, the process of a transportation agency redefining its goals is not very easily achieved. Thus, research that attempts to address sustainability for existing goals is a valuable contribution that can also provide feedback, and raise awareness about how transportation agencies can further address sustainability issues.

CHAPTER VI
FINDINGS AND CONCLUSIONS

The primary goal of this thesis was to create a methodology for evaluating sustainability for a state-level transportation agency. The methodology was designed to be implemented for a specific highway, to make it relevant to regular transportation planning processes in an agency. A refined application of the MAUT was developed for this study, consisting of a framework of performance measures that are scaled and aggregated to obtain an indicator of sustainability. The findings and observations from the process are discussed in this chapter.

GENERAL FINDINGS

Applying Sustainable Transportation to Highways

From the literature review and survey of practice, sustainability of transportation systems is widely discussed and is of increasing significance. While there is a general consensus regarding what elements are to be addressed in terms of transportation sustainability, there are differences in how sustainability is defined and addressed among different transportation agencies and research initiatives.

Another issue to be considered is whether sustainability can be addressed for highways alone. It is generally recognized that for sustainability goals to be met, an overall reduction of automobile travel is desirable. However, there are many other aspects that can contribute to making the existing highway infrastructure more sustainable, ranging from land use, air quality impacts, transit availability, asset management, and funding sources. It is valuable to address these factors, given that highway travel is the predominant mode of transportation in the U.S..

Linking Sustainability Assessments to Planning Goals

A disconnect exists between the regular transportation planning process and sustainable transportation planning in most state-level transportation agencies. This barrier to the implementation of sustainable planning is addressed by linking the agency’s strategic plan goals to sustainability-related objectives. While this may narrow the scope of the sustainability objectives, it creates the opportunity to address progress toward agency goals in a sustainable manner, which is a valuable step toward making transportation planning more sustainable. The importance of the sustainability-related objectives developed in this research must be emphasized, as these help guide the planning process in a more sustainable direction. As discussed in previous chapters, this does not represent a total solution to sustainability issues, but rather provides a starting point for agencies to understand and further apply principles of sustainability at a higher level.

Performance Measure-Based Sustainability Evaluations

Performance indicators or performance measures are useful for evaluating progress toward set targets or goals. Significant research regarding performance indicators for sustainable transportation exists, though these are primarily aimed at higher-level policy making. While there are sustainability indicators and performance measures proposed for highways, these are not combined in a framework that can address transportation planning for individual facilities. The use of performance measures provided a beginning point for evaluating highway sustainability within the transportation planning paradigm.

Sustainability Evaluation Using Decision Theory

Decision theory deals with creating means of comparing attributes that may be expressed in different terms – to aid in decisions that involve a variety of considerations. For a set of selected performance indicators, the decision theory is useful to express all indicators on a common platform – to evaluate the relative sustainability of different planning scenarios. For this research, a process termed as the MAUT was used.

The steps involved in the MAUT process included the evaluation of performance measures, scaling each performance measure to obtain a utility value, and aggregating the scaled measures into an indicator of sustainability. The scaling of utility functions was addressed in detail in this research, and a methodology based on the AHP is used to derive utility functions for selected measures.

Case Study

The sustainability evaluation methodology developed is tested for a case study section of US 281 in San Antonio, Texas. Two scenarios, representing conditions of the study section in 2005 (base case scenario) and 2025 (future case scenario) were compared. The progress toward sustainability with respect to each of the strategic plan goals, as well as for individual links on the study section was evaluated in the analysis. From the results of evaluation, it is observed that, overall, sustainability decreases in the future case scenario. This can be attributed to the increased traffic on the section. While the analysis did not look a project alternatives or construction options, it provides insight into how different factors associated with a project affect progress toward sustainability, and the extent of the impact of various attributes.

Possible Applications of Methodology

The methodology developed in this research has wide applicability. It can be used to identify specific links on a given roadway that perform worse with respect to sustainability. Different projects or alternative future scenarios can be compared, or the relative levels of sustainability can be assessed for different highways.

However, a significant contribution of this research is also in demonstrating how sustainability can be approached and assessed scientifically. Thus, this research can also serve to create awareness among transportation agencies, and provide a platform for further research.

CONCLUDING REMARKS

The following points provide a summary of the research and the results/findings.

- This research provides a means of evaluating sustainable progress toward transportation planning goals.

- While the scope of the analysis is restricted to highways, the methodology provides insight into how the sustainability of an existing highway can be improved, and the impact a more multimodal transportation system could have on the sustainability of a particular highway.
- A more detailed and scientific approach is used for the development of the MAUT-based evaluation methodology, particularly for the scaling of attribute utilities. A methodology to derive non-linear utility scaling was proposed and performed for selected performance measures.
- A case study analysis for a section of US 281 indicated how the methodology could be used to identify goals that need to be addressed with respect to sustainability, as well as identify problematic links along the study section.

In conclusion, the research conducted creates a more robust multi-criteria decision-making methodology for sustainability evaluation. The methodology addresses sustainability in a manner that allows for its integration into the transportation planning process. While this methodology is structured based on a set of planning goals that are created at a higher (agency-wide) level, the results from this form of analysis can also be used for evaluating agency goals with respect to sustainability, and feed into a process that can reevaluate those higher-level goals.

SCOPE FOR FURTHER RESEARCH

Based on the findings and conclusions, the following recommendations are made to further explore how performance measurement-based decision analysis can be used in evaluating highway sustainability.

- The methodology developed in this research could be applied to compare multiple highways, or to compare multiple future alternatives for a specific highway.
- The selection of sustainability indicators was constrained by the scope of the analysis, as well as by data availability. The inclusion of indicators that

address quality-of-life issues (e.g., job opportunities, walkability, commute times) is desirable, though more difficult to implement.

- The process of deriving non-linear utility functions was conducted for selected performance measures. A more detailed analysis of the relative usefulness of linear versus non-linear scaling is recommended.
- In this analysis, a single set of weights were derived from a workshop process and used. A sensitivity analysis to determine how the assignment of different weights affects the sustainability evaluation would also be a useful exercise.

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APPENDIX A

SCALING VALUES FOR CRASH ESTIMATION

- The following plots represent crash frequencies (annual severe crashes per mile) for a 3-year period from 1999 to 2001 on Texas roadways.
- The crash frequencies are plotted versus ADT for different road types and lane widths, and used to estimate the scaling values for the analysis.
- The scaling values selected are presented in Chapter IV. Figures A.1 to A.12 show the scatter plots that formed the basis for selecting these values.

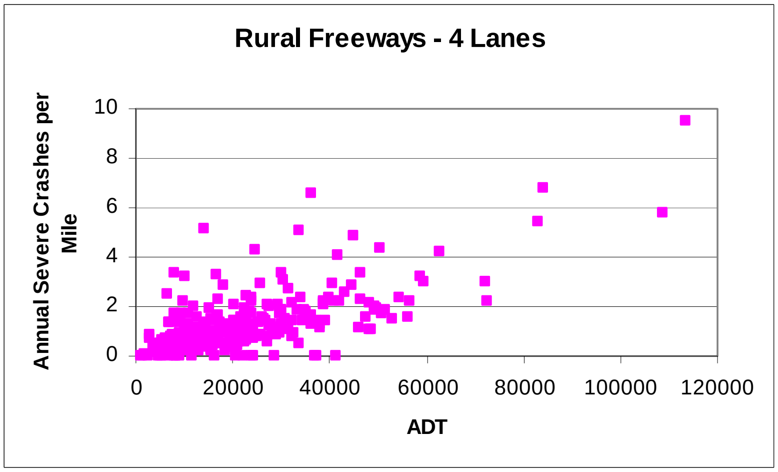

Figure A. 1 Plot of Crash Frequencies for 4-lane Rural Freeways.

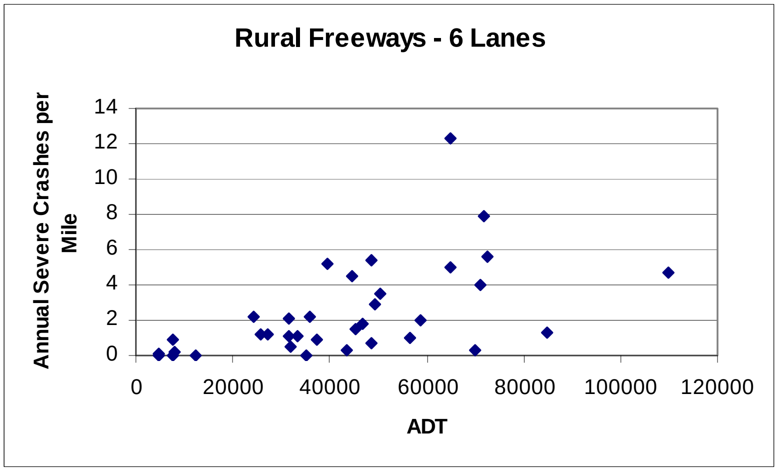

Figure A. 2 Plot of Crash Frequencies for 6-lane Rural Freeways.

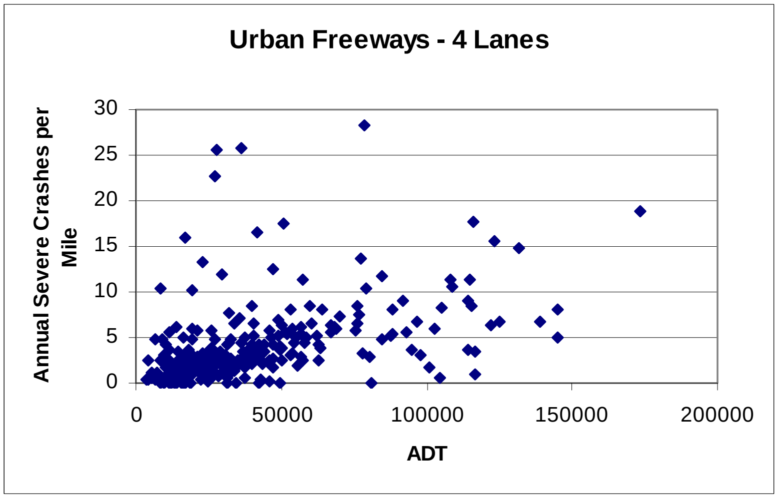

Figure A. 3 Plot of Crash Frequencies for 4-lane Urban Freeways.

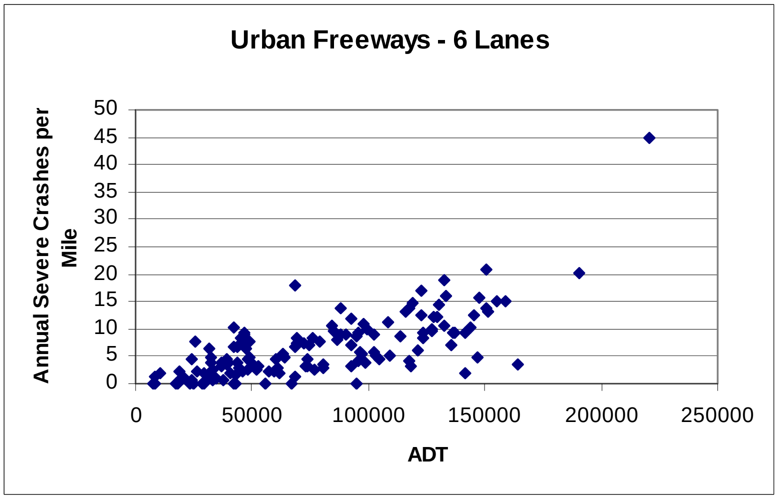

Figure A. 4 Plot of Crash Frequencies for 6-lane Urban Freeways.

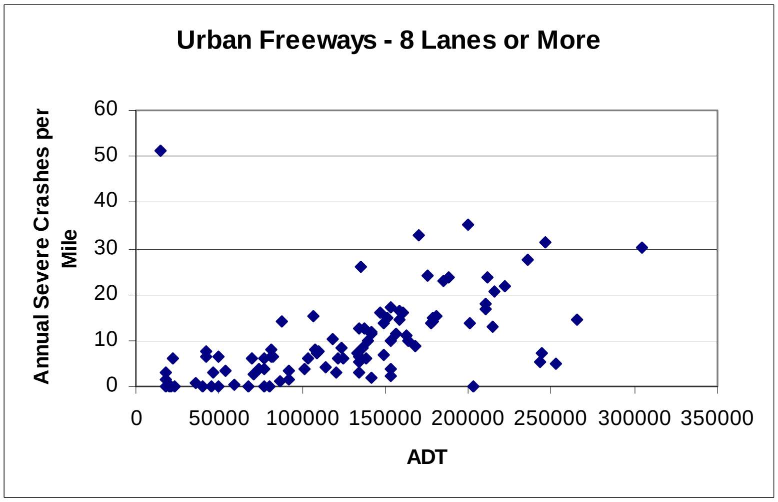

Figure A. 5 Plot of Crash Frequencies for 8-lane Urban Freeways.

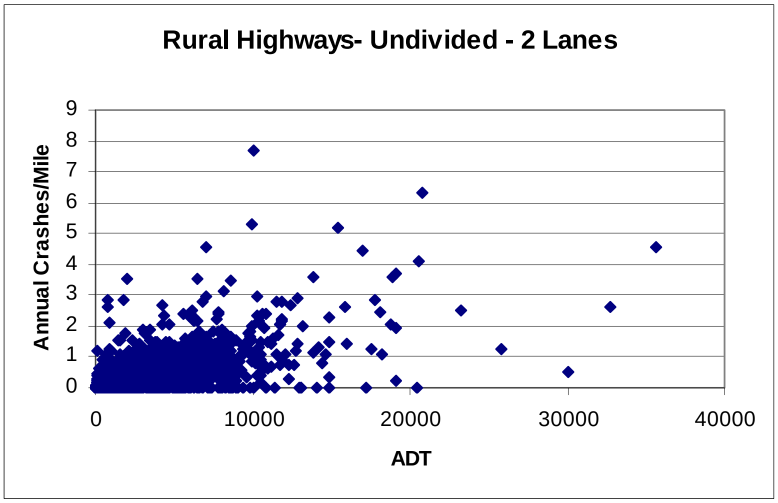

Figure A. 6 Plot of Crash Frequencies for 2-lane Undivided Rural Highways.

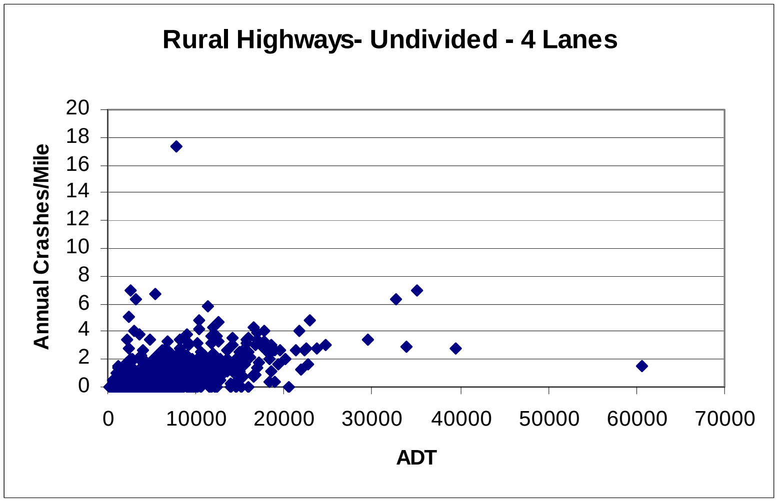

Figure A. 7 Plot of Crash Frequencies for 4-lane Undivided Rural Highways.

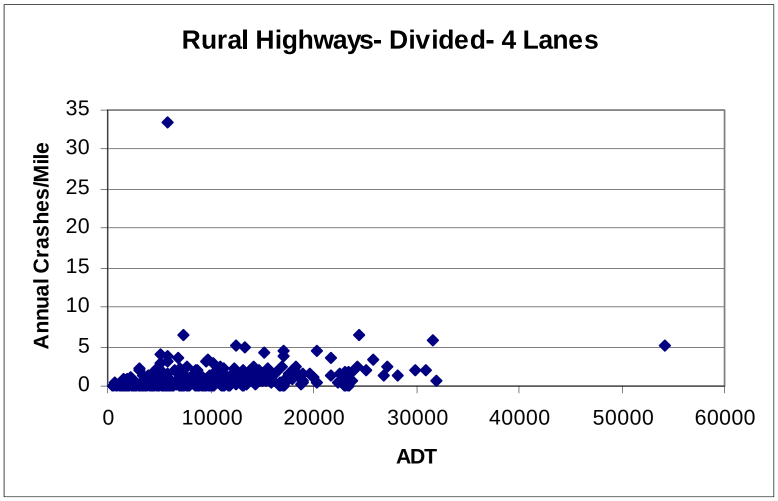

Figure A. 8 Plot of Crash Frequencies for 4-lane Rural Highways with Depressed Median.

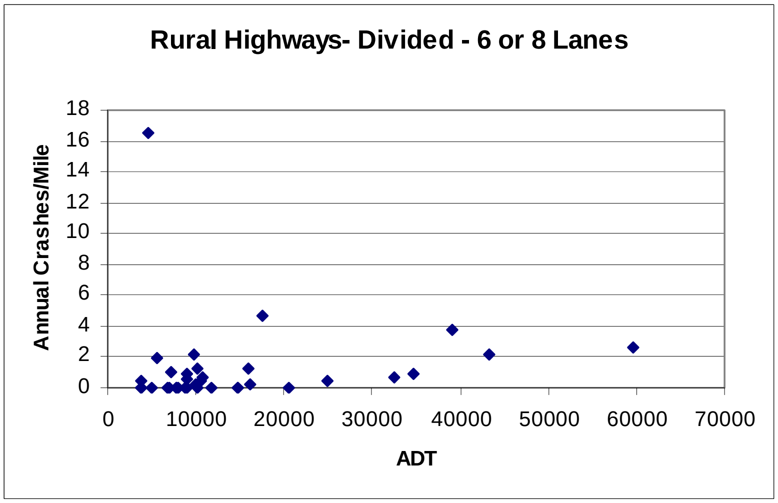

Figure A. 9 Plot of Crash Frequencies for 6-8-lane Rural Highways with Depressed Median.

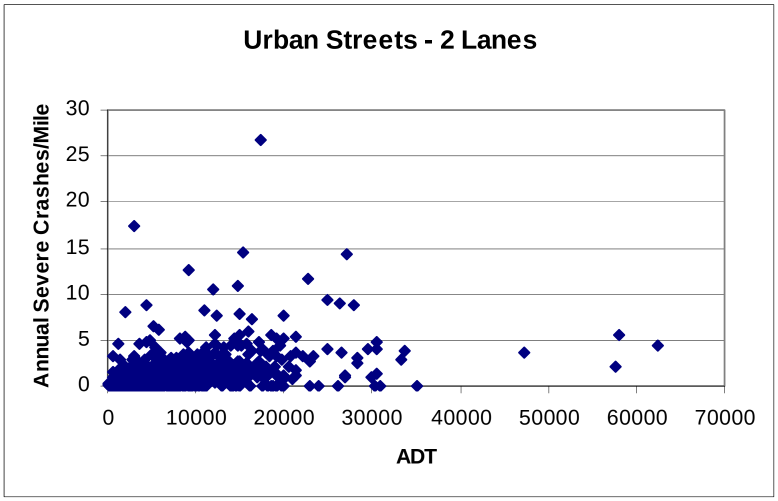

Figure A. 10 Plot of Crash Frequencies for 2-lane Urban Streets.

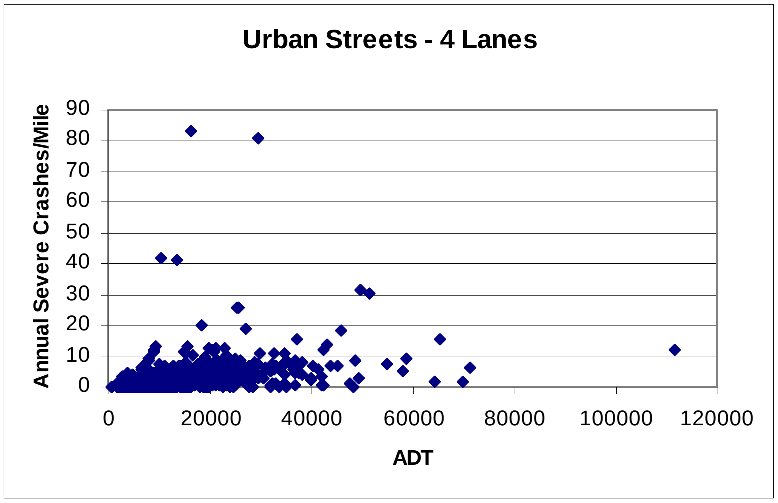

Figure A. 11 Plot of Crash Frequencies for 4-lane Urban Streets.

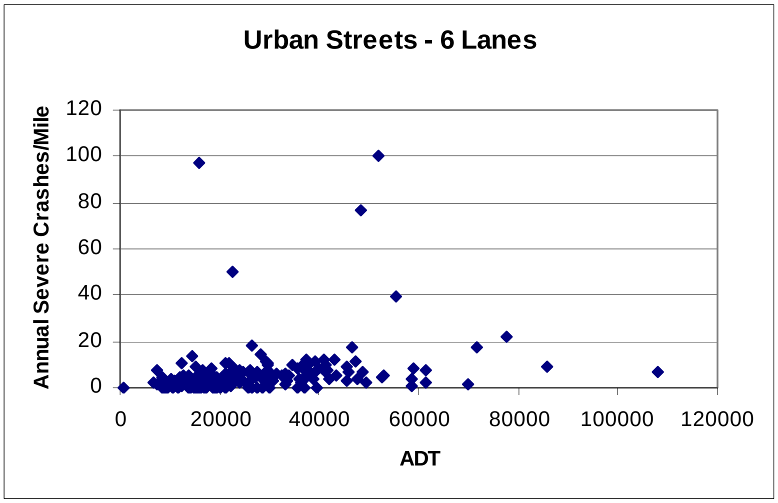

Figure A. 12 Plot of Crash Frequencies for 6-lane Urban Streets.

CRASH ESTIMATION PROCEDURE

- The crash estimation procedure is based on the *Interim Roadway Safety Design Workbook* and is carried out for three roadway types – freeways, urban streets and rural highways.
- The procedure used in this research has three steps:
  - Estimate annual severe crashes along roadway length.
  - Estimate annual severe crashes for all at-grade intersections along length of roadway.
  - Combine the roadway and intersection crashes and divide by roadway length to obtain annual frequency of severe crashes (annual severe crashes per mile).

Estimating Crashes along Roadway Length

The formula for estimating crashes along a roadway length is given in Equation A.1. The base crash rates for freeways, rural highways, and urban streets are given in Tables A.1-A.3.

$$\textit{Total Annual Severe Crashes} = 0.000365 \times \textit{Base} \times \textit{ADT} \times L \qquad (A.1)$$

Where,

Base = base crash rate (crashes per million VMT)

ADT= average daily traffic

L= roadway length

Table A. 1 Base Crash Rates for Freeways.

Area Type	**Attributes**	**Base Crash Rate, severe crashes/MVMT**		
	Through Lanes	**4**	**6**	**8-10**
Urban		0.24	0.36	0.54
Rural		0.14	0.21	-

Table A. 2 Base Crash Rates for Rural Highways.

Median Type	**Attributes**	**Base Crash Rate, severe crashes/MVMT**		
	Through Lanes	**2**	**4**	**6**
Undivided/Surfaced		0.2	0.3	-
Depressed		-	0.21	0.32-

Table A. 3 Base Crash Rates for Urban Streets.

Adjacent Land Use	Attributes	Base Crash Rate, severe crashes/MVMT				
	Median Type	Undivided or Two Way Left Turn Lane Median			Raised-Curb Median	
	Through Lanes	2	4	6	4	6
Undivided/Surfaced		0.95	1.04	1.15	0.75	0.83
Depressed		0.41	0.45	0.5	0.41	0.45

Application of Accident Modification Factors

Accident modification factors (AMFs) are used to reflect the impact certain geometric or design features have on the base crash rate. The base crash rate is adjusted by multiplying it by a set of AMFs. The value of the AMF for a particular feature depends upon how much it deviates from a standard defined value and takes a default value=1.

In this research, AMFs have been considered for a range of features for each road type. However, this particular set of calculations does not incorporate these AMFs, but instead assumes the existence of default characteristics (such as standard lane widths and shoulder widths, etc). The list of possible AMFs that can be applied are given below. These may be used when a more detailed analysis of crashes is warranted.

- For freeways –
    - Grade
    - Lane width
    - Outside shoulder width
    - Inside shoulder width
    - Median width
- For Rural Highways–
    - Grade
    - Lane width
    - Outside shoulder width
    - Inside shoulder width
    - Median width
    - Presence of a two way left turn lane

  - Driveway density
- For Urban Streets–
  - Lane width
  - Shoulder width
  - Driveway density
  - Presence of a two way left turn lane
  - Truck percentage

Estimating Crashes at Intersections

Intersection crashes are considered only for at-grade intersections (rural highways or urban streets). The formula for estimating crashes for each intersection is given in Equation A.2. The base crash rates for intersections on rural highways and urban streets, for three-leg and four-leg intersections are given in Tables A.4 to A.7.

$$\text{Total Annual Severe Crashes} = 0.000365 \times \text{Base} \times (Q_{major} + Q_{minor}) \qquad (A.2)$$

Where,

Base = base crash rate (crashes per million entering vehicles)
Q_{major}= ADT on major road
Q_{minor}= ADT on minor road

Table A. 4 Base Intersection Crash Rates for 3-Leg Rural Intersections.

For Unsignalized Intersections (crashes per MEV)					
ADT	**Ratio of Minor to Major ADT**				
	0.05	**0.1**	**0.15**	**0.2**	**0.25**
5000	0.1	0.14	0.16	0.18	0.19
10000	0.13	0.18	0.21	0.23	0.25
15000	0.15	0.2	0.24	0.26	0.28
20000	0.17	0.23	0.23	0.26	0.28
>25000	0.18	0.2	0.25	0.28	0.3
For Signalized Intersections (crashes per MEV)					
ADT	**Ratio of Minor to Major ADT**				
	0.05	**0.1**	**0.15**	**0.2**	**0.25**
5000	0.08	0.11	0.14	0.16	0.17
10000	0.1	0.15	0.18	0.2	0.22
15000	0.12	0.17	0.21	0.23	0.25
20000	0.13	0.19	0.23	0.26	0.28
25000	0.14	0.2	0.25	0.28	0.3
30000	0.15	0.22	0.26	0.3	0.33
40000	0.17	0.24	0.29	0.33	0.36
>50000	0.18	0.26	0.32	0.36	0.39

Table A. 5 Base Intersection Crash Rates for 4-Leg Rural Intersections.

For Unsignalized Intersections (crashes per MEV)					
	Ratio of Minor to Major ADT				
ADT	**0.1**	**0.3**	**0.5**	**0.7**	**0.9**
5000	0.18	0.26	0.3	0.31	0.32
10000	0.2	0.3	0.34	0.36	0.36
15000	0.22	0.33	0.37	0.39	0.4
20000	0.23	0.32	0.37	0.4	0.42
> 25000	0.25	0.33	0.39	0.42	0.44
For Signalized Intersections (crashes per MEV)					
ADT	**Ratio of Minor to Major ADT**				
	0.1	**0.3**	**0.5**	**0.7**	**0.9**
5000	0.15	0.24	0.28	0.3	0.31
10000	0.17	0.28	0.32	0.35	0.36
15000	0.18	0.3	0.35	0.38	0.39
20000	0.2	0.32	0.37	0.4	0.42
25000	0.2	0.33	0.39	0.42	0.44
30000	0.21	0.35	0.41	0.44	0.45
40000	0.23	0.37	0.43	0.46	0.48
>50000	0.24	0.38	0.45	0.49	0.5

Table A. 6 Base Intersection Crash Rates for 3-Leg Urban Intersections.

For Unsignalized Intersections (crashes per MEV)				
Ratio of Minor to Major ADT				
0.05	**0.1**	**0.15**	**0.2**	**0.25**
0.18	0.21	0.22	0.22	0.23
For Signalized Intersections (crashes per MEV)				
Ratio of Minor to Major ADT				
0.05	**0.1**	**0.15**	**0.2**	**0.25**
0.12	0.15	0.17	0.18	0.19

Table A. 7 Base Intersection Crash Rates for 4-Leg Urban Intersections.

For Unsignalized Intersections (crashes per MEV)					
	Ratio of Minor to Major ADT				
ADT	**0.1**	**0.3**	**0.5**	**0.7**	**0.9**
5000	0.25	0.29	0.28	0.27	0.26
10000	0.23	0.26	0.26	0.25	0.24
15000	0.22	0.24	0.24	0.23	0.22
20000	0.21	0.2	0.21	0.21	0.21
> 25000	0.2	0.19	0.2	0.21	0.2
For Signalized Intersections (crashes per MEV)					
ADT	**Ratio of Minor to Major ADT**				
	0.1	**0.3**	**0.5**	**0.7**	**0.9**
5000	0.19	0.24	0.26	0.26	0.26
10000	0.17	0.22	0.23	0.23	0.23
15000	0.16	0.21	0.22	0.22	0.22
20000	0.15	0.2	0.21	0.21	0.21
25000	0.15	0.19	0.2	0.21	0.2
30000	0.14	0.19	0.2	0.2	0.2
40000	0.14	0.18	0.19	0.19	0.19
>50000	0.13	0.17	0.18	0.19	0.18

Inputs for Estimating Crashes for Study Section

Table A.8 below provides the details for each link on the study section used to estimate crash frequencies for the case study. As mentioned earlier, only base rates were considered for roadway lengths and intersections. AMFs were not considered.

Table A. 8 Crash Estimation Inputs for Study Section.

Link	Description	Base Case		Future Case	
		Roadway Type	Intersection Details	Roadway Type	Intersection Details
1	410-Bitters	Urban Freeway – 6 lanes	N/A	Urban Freeway – 6 lanes	N/A
2	Bitters-Evans	Urban Freeway – 6 lanes	N/A	Urban Freeway – 6 lanes	N/A
3	Evans-Bulverde	Rural Highway– 4 lanes, depressed median	▪ Evans: 4-leg signalized ▪ Stone Oak: 4-leg signalized ▪ Overlook: 3-leg unsginalized ▪ Summerglen: 3-leg unsignalized ▪ Mountain Lodge: 4-leg unsignalized ▪ Marshall: 4-leg unsignalized	Urban Freeway – 6 lanes	N/A
4	Bulverde-Comal County	Rural Highway– 4 lanes, depressed median	▪ Bulverde: 4-leg signalized ▪ Borgfeld: 3-leg signalized	Urban Freeway – 6 lanes	N/A

APPENDIX B

CALCULATION OF EXTREME VALUES FOR TRUCK THROUGHPUT EFFICIENCY

- In order to obtain the extreme values for scaling of the truck throughput efficiency, the measure was calculated for a range of ADTs and truck percentages.
- The range of ADT considered was from 5000 to 25000 ADT per lane. The range of truck percentages considered was from 2% to 20%.
- Based on the calculation of throughput efficiency (Daily truck-miles per hour per lane), the minimum and maximum values were assigned as the worst and best case scenarios respectively. These values are calculated as 5640 and 170704 daily truck- miles per hour per lane, as shown in Table B.1.
- It can be observed that the optimum value for truck throughput does not correspond to the maximum truck percentage –this indicates the effect increased traffic and truck volumes have on the speed.
- Figure B.1 shows how the throughput efficiency varies with truck percentage for different ADT per lane values. It can be seen that the marginal gain in the throughput efficiency decreases as ADT increases, and that the values corresponding to an ADT per lane of 20000 are more than those corresponding to an ADT per lane of 25000. Thus, this performance measure does optimize truck throughput, and is not merely a surrogate measure for truck percentages.

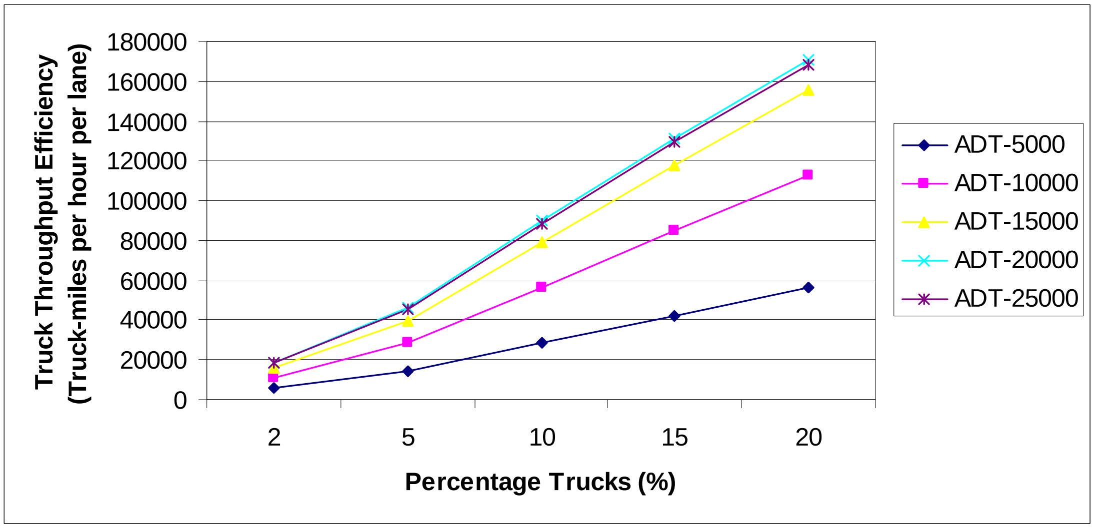

Figure B. 1 Variation of Truck Throughput Efficiency.

Table B. 1 Calculation of Truck Throughput Efficiency for Different ADT and Percent Trucks.

ADT/lane	Truck Percentage	No. of Trucks/lane	Equivalent ADT/lane (considering 1 truck = 1.5 pce)	Traffic Operating Speed (mph)	Truck Speed-6% less (mph)	Truck Throughput Efficiency (Daily truck-miles per hour per lane)
5000	2	100	5050	60.0	56.4	5,640
	5	250	5125	60.0	56.4	14,100
	10	500	5250	60.0	56.4	28,200
	15	750	5375	60.0	56.4	42,300
	20	1000	5500	60.0	56.4	56,400
10000	2	200	10100	60.0	56.4	11,280
	5	500	10250	60.0	56.4	28,200
	10	1000	10500	60.0	56.4	56,400
	15	1500	10750	60.0	56.4	84,600
	20	2000	11000	60.0	56.4	112,800
15000	2	300	15150	56.4	53.0	15,895
	5	750	15375	56.2	52.8	39,595
	10	1500	15750	55.8	52.5	78,713
	15	2250	16125	55.5	52.2	117,356
	20	3000	16500	55.2	51.8	155,523
20000	2	400	20200	49.5	46.6	18,627
	5	1000	20500	48.9	45.9	45,919
	10	2000	21000	47.7	44.8	89,676
	15	3000	21500	46.6	43.8	131,271
	20	4000	22000	45.4	42.7	170,704
25000	2	500	25250	39.1	36.8	18,393
	5	1250	25625	38.6	36.3	45,340
	10	2500	26250	37.7	35.4	88,536
	15	3750	26875	36.8	34.6	129,588
	20	5000	27500	35.9	33.7	168,495
Minimum Value						**5,640**
Maximum Value						**170,704**

APPENDIX C

MOBILE6 EMISSIONS RATES – FOR NO_X, CO, AND VOC

- The emissions rates considered for the base and future cases, obtained from the MOBILE6 emissions model are presented in Table C.1 and Table C.2 respectively.
- The emissions rates are expressed as grams per ADT, accounting for the fleet mix and emissions rates for individual vehicle types.

Table C. 1 MOBILE6 Emissions Rates for Base Case (2005).

Speed (mph)	Total Emissions per ADT (grams/mile)		
	VOC	**Nox**	**CO**
2.5	6.62	3.05	27.03
5	2.27	2.68	15.35
10	1.04	2.06	8.98
15	0.70	1.72	7.08
20	0.55	1.63	6.42
25	0.47	1.56	6.17
30	0.42	1.53	6.04
35	0.37	1.52	6.11
40	0.34	1.54	6.50
45	0.31	1.60	6.91
50	0.29	1.69	7.34
55	0.27	1.82	7.79
60	0.25	2.01	8.27
65	0.24	2.28	8.77

Table C. 2 MOBILE6 Emissions Rates for Future Case (2025).

Speed (mph)	Total Emissions per ADT (grams/mile)		
	VOC	**Nox**	**CO**
2.5	2.40	0.61	14.82
5	0.89	0.52	8.49
10	0.43	0.35	4.90
15	0.29	0.27	3.77
20	0.22	0.26	3.33
25	0.19	0.26	3.20
30	0.17	0.25	3.11
35	0.15	0.25	3.11
40	0.14	0.25	3.32
45	0.13	0.26	3.53
50	0.12	0.27	3.75
55	0.11	0.28	3.97
60	0.11	0.30	4.22
65	0.10	0.33	4.47

Emissions Rates for CO_2

- While the MOBILE6 model does provide emissions rates for CO_2, these rates are not commonly used in emissions modeling applications.
- The CO_2 emissions rates used in this study are obtained from emissions testing conducted by the Texas Transportation Institute.
- Based on emissions rates for various vehicle types and knowledge of the fleet mix, emissions rates are obtained, as shown in Table C.3. The CO_2 emissions rates are considered to be the same for the base and future cases.

Table C. 3 Emissions Rates for CO_2.

Speed (mph)	Total Emissions per ADT (grams/mile)
2.5	1137.90
5	1084.38
10	984.87
15	895.36
20	815.86
25	746.38
30	686.90
35	637.44
40	597.99
45	568.55
50	549.12
55	539.70
60	540.30
65	550.90

CALCULATION OF EXTREME VALUES FOR DAILY EMISSIONS

- To obtain the extremes for the scaling of emissions measures, the daily emissions were calculated for a range of ADT values.
- Peak and off-peak operating speeds to obtain the emissions rates were considered to be 35 mph and 60 mph respectively (corresponding to the extreme values that can be obtained in the speed estimation process). The emissions rate for each pollutant for peak and off-peak conditions are shown in Table C.4.

- For each level of ADT, two daily emissions values were calculated –a low estimate, in which 20% of the total ADT occurs under peak conditions and a high estimate, where 40% of the total ADT occurs under peak conditions.
- The range of ADT values used was from 5000 (considered to represent traffic on a rural road) to 150000 (considered to represent a 6-lane, high volume facility). Based on this, daily emissions were estimated. To obtain combined emissions for the case of VOC, NOx, and CO, and for ozone precursors (VOC and NOx only), the individual emissions were combined based on weights derived from their respective damage costs.
- The calculated high and low estimates for combined VOC, NOx and CO emissions, for CO_2 emissions, and for ozone precursor (NOx and VOC) emissions are shown in Table C.5 and Table C.6 for base and future case respectively.

Table C. 4 Peak and Off-Peak Emissions.

Base Case Emissions at Peak Speed (gm/ADT/mile)			
VOC	Nox	CO	CO_2
0.25	2.01	8.27	540.30
Base Case Emissions at Off- Peak Speed (gm/ADT/mile)			
VOC	Nox	CO	CO_2
0.37	1.52	6.11	637.44
Future Case Emissions at Peak Speed (gm/ADT/mile)			
VOC	Nox	CO	CO_2
0.11	0.30	4.22	540.30
Future Case Emissions at Off- Peak Speed (gm/ADT/mile)			
VOC	Nox	CO	CO_2
0.15	0.25	3.11	637.44

Table C. 5 Calculation of Total Daily Emissions for Scaling – Base Case.

ADT	Combined Nox, VOC,CO (grams/mile)		CO$_2$ (grams/mile)		Combined Ozone Precursors (grams/mile)	
	Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
5000	5761	6019	3090065	2992920	5338	5567
15000	17283	18058	9270195	8978759	16015	16701
25000	28805	30097	15450325	14964598	26692	27835
35000	40327	42136	21630455	20950437	37368	38969
45000	51849	54175	27810585	26936276	48045	50103
55000	63370	66214	33990715	32922115	58722	61237
65000	74892	78253	40170846	38907954	69398	72371
75000	86414	90291	46350976	44893793	80075	83505
85000	97936	102330	52531106	50879632	90751	94639
95000	109458	114369	58711236	56865472	101428	105773
105000	120980	126408	64891366	62851311	112105	116907
115000	132502	138447	71071496	68837150	122781	128041
125000	144024	150486	77251626	74822989	133458	139175
150000	172828	180583	92701951	89787587	160150	167010

Table C. 6 Calculation of Total Daily Emissions for Scaling –Future Case.

ADT	Combined Nox, VOC,CO (grams/mile)		CO$_2$ (grams/mile)		Combined Ozone Precursors (grams/mile)	
	Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
5000	1289	1315	3090065	2992920	1048	1057
15000	3866	3945	9270195	8978759	3143	3171
25000	6444	6576	15450325	14964598	5239	5286
35000	9022	9206	21630455	20950437	7334	7400
45000	11599	11836	27810585	26936276	9429	9514
55000	14177	14467	33990715	32922115	11525	11629
65000	16754	17097	40170846	38907954	13620	13743
75000	19332	19727	46350976	44893793	15716	15857
85000	21910	22358	52531106	50879632	17811	17971
95000	24487	24988	58711236	56865472	19906	20086
105000	27065	27618	64891366	62851311	22002	22200
115000	29642	30249	71071496	68837150	24097	24314
125000	32220	32879	77251626	74822989	26193	26429
150000	38664	39455	92701951	89787587	31431	31714

- From Table C.5 and Table C.6, the following scaling extremes are obtained:
    - Combined VOC, NOx, and CO Emissions:
        - Best – 1289 grams/mile/day
        - Worst– 180583 grams/mile/day
    - CO_2 Emissions:
        - Best – 2992920 grams/mile/day
        - Worst– 92701951 grams/mile/day
    - Ozone Precursor Emissions:
        - Best – 1048 grams/mile/day
        - Worst – 167011 grams/mile/day
        - Maximum Difference– 165963 grams/mile/day

APPENDIX D

PROCESS OF MAKING COMPARISONS FOR THE AHP

The process of deriving scores for pair-wise comparisons in the AHP is described using the example relating to emissions reduction. Scenario X could be defined as reducing daily emissions from 180.5 kg/mile to 125 kg/mile, while Scenario Y could be defined as reducing emissions from 125 kg/mile to 100 kg/mile. Based on knowledge of the performance measure and its variation, it is possible to compare the relative desirability or importance of achieving the scenarios. To facilitate an understanding of this concept, the two scenarios can be considered as applicable to two similar roadways. Then, decision makers would need to identify which roadway's emissions they would choose to improve, and how strongly they prefer it (which is indicative of the ease with which they are able to make the choice). This strength of preference is expressed on a numerical scale from 1-9, using a set of guidelines as devised by Saaty, the creator of the AHP, which are a follows:

- Score 1 – Both scenarios are equally important
- Score 3 – One scenario is weakly more important than the other
- Score 5– One scenario is strongly more important than the other
- Score 7 – One scenario is demonstrably more important than the other
- Score 9 – One scenario is absolutely more important than the other

The even numbers in between can also be used to indicate judgments that lie between two levels. For example, for the Scenarios X and Y mentioned above, it is probable that the decision maker would choose Scenario X over Scenario Y, since it involves reduction in emissions much closer to the worst possible value. However, the strength of preference in this case may not be very high, as Scenario Y also involves fairly high emissions levels. However, if Scenario Y instead referred to reduction in emissions from 26.5 kg/mile to 1.5 kg/mile (very close to the best case), the strength of preference of X over Y would probably be much higher.

For obtaining responses from the decision makers, a questionnaire with the following format was used (an example response is filled in to illustrate):

Indicate the preferred scenario:

[✓ X]	Y

Indicate Strength of Preference:

1	3	[✓ 5]	7	9

This choice indicates that the respondent believes that **Scenario X is strongly more important** than Scenario Y. The results from a set of pair-wise comparisons are used to populate the AHP matrix and derive a utility curve for emissions.

COMBINING RESPONSES FROM INDIVIDUAL DECISION MAKERS

In this research, responses for individual decision makers were obtained, using which individual utility functions could be derived from each. It was observed that there were some differences in the utilities derived from each set of responses. Moreover, some sets of responses had high consistency index values (indicating a lack of consistency). Since the utility curves for most decision makers followed a very similar pattern, a final AHP matrix was constructed, based on the responses, with slight modifications made to adjust consistencies. From this, a revised set of points on a utility curve was obtained, and a utility function was fit to these points. The points on the utility curve and the consistency indices for the emissions measure and the high occupancy measure for individual decision makers are tabulated in Table D.1 and Table D.2 respectively. Plots of the utility curves for each are shown in Figure D.1 and Figure D.2 respectively.

Table D. 1 Utilities Derived From Individual Responses for Scaling Emissions Measure.

Daily Combined VOC, CO, and NO_x Emissions (kg/mile)	**Scaled Utility Values for Each Decision Maker**					
	DM1	**DM2**	**DM3**	**DM4**	**DM5**	**DM6**
180.50	0.00	0.00	0.00	0.00	0.00	0.00
135.70	0.63	0.66	0.21	0.63	0.05	0.66
90.89	0.87	0.83	0.42	0.87	0.19	0.86
46.09	0.96	0.94	0.91	0.96	0.52	0.91
1.28	1.00	1.00	1.00	1.00	1.00	1.00
Consistency Index	0.26	0.14	0.05	0.15	0.45	0.23
Consistency Ratio	0.29	0.16	0.06	0.17	0.50	0.25

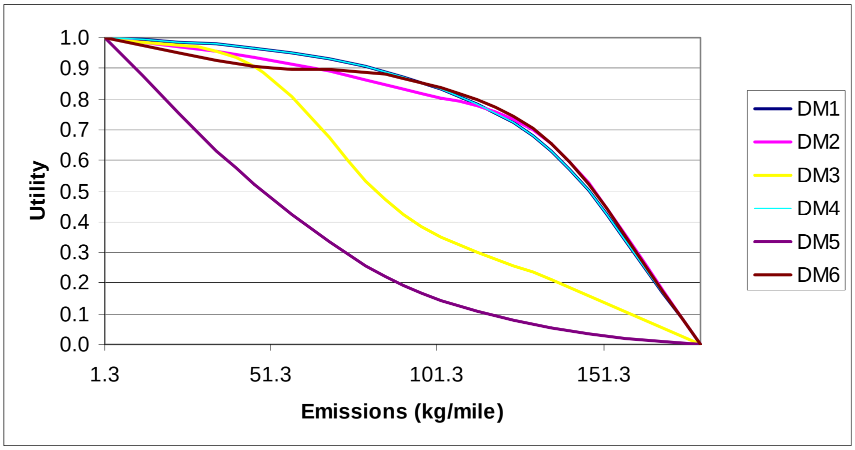

Figure D. 1 Shape of Utility Curve for Individual Responses for Total Daily Emissions.

Table D. 2 Utilities Derived From Individual Responses for Scaling High-Occupancy Measure.

Proportion of Person-Miles Traveled on non-SOVs	**Scaled Utility Values for Each Decision Maker**					
	DM1	**DM2**	**DM3**	**DM4**	**DM5**	**DM6**
25.00%	0.00	0.00	0.00	0.00	0.00	0.00
38.00%	0.05	0.68	0.07	0.54	0.04	0.66
51.00%	0.13	0.84	0.67	0.81	0.14	0.87
64.00%	0.38	0.94	0.88	0.94	0.48	0.95
77.00%	1.00	1.00	1.00	1.00	1.00	1.00
Consistency Index	0.16	0.17	0.10	0.07	0.16	0.16
Consistency Ratio	0.18	0.19	0.11	0.07	0.18	0.18

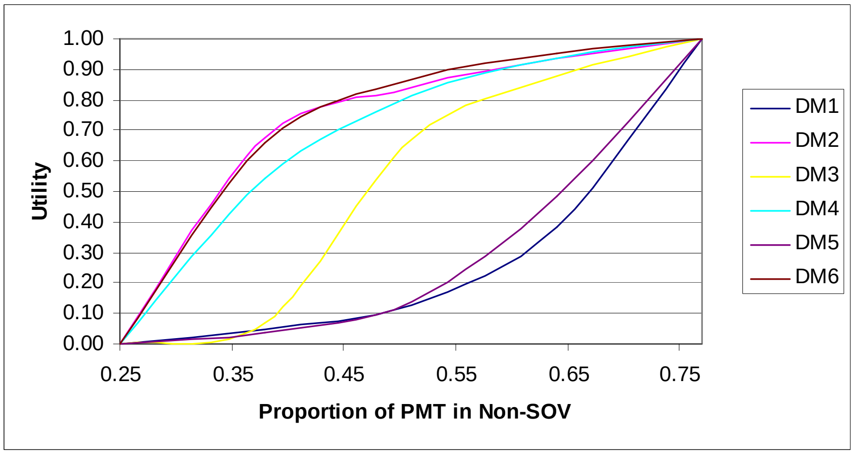

Figure D. 2 Shape of Utility Curve for Individual Responses for Proportion of Non-SOV Travel.

DERIVATION OF UTILITY FUNCTIONS

Based on the points on the utility curve derived from the final AHP matrix (presented in Chapter IV), the utility functions are derived for the two performance measures. The functional form assumed is:

$$y = a + b \times e^{-cx}$$

The parameters for each of the utility curves are optimized to minimize the sum of squared error. The final derived functions are presented in Chapter IV. Tables D.3 through D.5 show the optimized parameter values and sum of squared error for both the fitted utility curves. Both results indicate a highly satisfactory fit.

Table D. 3 Optimized Parameter Values for Non-Linear Utility Curves.

Parameter	Optimized Parameter Values	
	Total Daily Emissions	Proportion of Non-SOV Travel
a	1.019	1.059
b	-0.018	-4.249
c	-0.022	5.558

Table D. 4 Sum of Squared Error for Fitted Utility Function – Total Daily Emissions.

Daily Emissions (kg/mile)	***Scaled Utility from Derived from AHP***	***Predicted Utility from Curve Fitting***	***Squared Error***
180.50 kg/mile	0.00	0.00	1.08E-13
135.70 kg/mile	0.64	0.64	1.28E-05
90.89 kg/mile	0.89	0.88	5.08E-05
46.09 kg/mile	0.96	0.97	1.73E-05
1.28 kg/mile	1.00	1.00	1.68E-21
		Sum of Squared Error	8.09E-05

Table D. 5 Sum of Squared Error for Fitted Utility Function –Non-SOV Travel.

Proportion of Non-SOVs	***Scaled Utility from Derived from AHP***	***Predicted Utility from Curve Fitting***	***Squared Error***
25.00 %	0.00	0.00	3.37E-13
38.00 %	0.54	0.54	1.99E-05
51.00 %	0.81	0.81	3.13E-05
64.00 %	0.94	0.94	1.69E-09
77.00 %	1.00	1.00	1.68E-15
		Sum of Squared Error	5.12E-05

VITA

Tara Lakshmi Ramani was born in Chennai, India. After graduating from high school in 2001, she entered Anna University to study engineering. She received a Bachelor's Degree in civil engineering in 2005, graduating at the top of her class, with academic distinction. After working for a private highway design and consulting firm in India, Ms. Ramani entered the Transportation Engineering program at Texas A&M University in 2006. She received a Master of Science Degree in civil engineering in August 2008. Her research interests include transportation planning, environmental concerns, socio-economic issues related to transportation, and performance measures related to transportation.

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