Sustainability Enhancement Tool for State Departments of Transportation Using Performance Measurement

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Abstract: The goal of this paper was to develop a performance measurement–based approach for transportation agencies, such as state departments of transportation, to evaluate and enhance sustainability. This research proposes a performance measurement–based framework and evaluation methodology for sustainable transportation, linked to agency strategic planning goals. The methodology was applied and tested for the Texas Department of Transportation (TxDOT). This sustainability enhancement methodology is implemented within the highway-corridor planning process. The research identified 12 performance measures, including measures of congestion, safety, alternative modes, and air quality, to address the goals and objectives in TxDOT's strategic plan. The multiattribute utility theory (MAUT) decision-making approach was applied to quantify and normalize the selected performance measures and calculate sustainability index values for current and predicted future corridor conditions. This paper also presents the results from a pilot application of the methodology for a section of US-281 in San Antonio, Texas. The findings made it possible to identify specific performance measures and specific portions of the corridor that needed improvement to enhance the overall sustainability. This research provides a useful tool to assess the relative sustainability of transportation corridors now and in the future. **DOI: 10.1061/(ASCE)TE.1943-5436.0000255.** *© 2011 American Society of Civil Engineers.*

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Introduction

Sustainability can be broadly viewed as relating to the recognition, evaluation, and attempted mitigation of long-term impacts of human or developmental activity. Transportation plays a major role in today's world and is an essential extension of almost any human activity. Sustainability concerns about the role of transportation relate to greenhouse gas emissions, fuel-resource depletion, and toxic pollution, as well as transportation costs and the equity of transportation policy. Given these concerns, promoting transportation sustainability is a logical step toward overall sustainable development.

Sustainable transportation needs to consider the three dimensions of sustainability: environment, economy, and society. Agencies, such as state departments of transportation (DOTs), relate to sustainability to a certain extent mostly of broad goals, such as the provision of safe and efficient transportation systems, adequate access and mobility, and protection of the environment, as well as by their contributions to overall economic development in the state. The reality, however, is that transportation agencies, such as DOTs, rarely address the goals of sustainable transportation in a comprehensive manner. Often, only selected aspects of sustainability (for example, safety) are focused on.

Successful implementation of sustainable transportation requires the understanding, quantification, and application of the basic concepts of sustainability as they relate to transportation (Zietsman and Rilett 2002). The use of performance measurement is relevant in this area because it allows objective and consistent measurement of progress toward sustainability goals. From the perspective of transportation agencies such as DOTs, there is a need for the development of a practical approach to sustainability evaluation and enhancement.

Research Objectives

This paper presents a performance measurement–based approach to assessing sustainability in the transportation context. It discusses a sustainability evaluation and enhancement methodology developed for highway-corridor planning, specifically for the Texas Department of Transportation (TxDOT). The methodology was implemented in the form of a user-friendly analysis tool for assessment of transportation corridors. The overall research goals were to develop sustainable transportation performance measures for TxDOT's strategic goals and to develop a methodology for the TxDOT to implement a more sustainable transportation system at the highway-corridor level. It is anticipated that the concepts and principles developed under this study can be applied to other state DOTs or used to address other aspects of sustainable transportation.

The project achieved its overall goal by addressing the following objectives:

- Development of a framework for evaluating sustainable transportation,

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- Development of relevant performance indicators/measures to capture the aspects and needs of sustainable transportation within this framework,
- Incorporation of these indicators/measures into a performance-measurement methodology and analysis tool that TxDOT can implement into regular practice,
- Development of a pilot application for a specific highway corridor, and
- Discussion of how the research can be implemented into broad transportation planning practice.

Research Scope

Although there has been a certain amount of research attempting to quantify transportation sustainability, there has been less discussion on how to measure sustainability within the regular functions of a transportation agency. The value of the results of this research lies in being able to link sustainability to the existing transportation planning process. This was done by defining an appropriate scope to this research project. The two main aspects that define the scope are

- Alignment of the framework and performance measures with TxDOT's strategic plan goals, and
- Focus on highway corridors.

Aligning the research measures and methodology with an agency's strategic goals helps reconcile the goals of sustainability with the agency's goals. This provides a useful starting point to address sustainability in a way that ensures agency buy-in. For this research, it was also helpful to align sustainable planning with the realities of transportation in the United States. The personal automobile is the most commonly used form of transportation for all types of trips and, consequently, most of the work carried out by state DOTs involves highway-corridor planning. Thus, selecting indicators relevant to highway-corridor planning and linking them to TxDOT's strategic goals helped make this research suitable for practical implementation.

Another feature of this research is the development of performance measures that can also be forecasted to allow for the comparison of current conditions with future scenarios, which further enhances the practical value of this research.

Outline of Paper

This paper contains sections on background and literature review, development of a performance-measurement framework, implementation of a decision-making methodology, concluding remarks, and recommendations for the scope of future work, acknowledgments, and references.

Background and Literature Review

This section covers five major topics relevant to the research goals of developing a performance-measurement framework and methodology for agencies, such as DOTs, to implement sustainability enhancements. These topics include a brief overview of the concepts of sustainability and sustainable development, a discussion of sustainability as applicable for transportation agencies, performance measurement for sustainable transportation, the characteristics of a good performance-measurement system, and the applicability of multicriteria decision-making methods for evaluating sustainability.

Sustainability and Sustainable Development

Numerous authors have provided definitions for sustainability, sustainable development, and sustainable transportation, and most of these are rooted in a 1987 report for the United Nations World Commission on Environment and Development (commonly referred to as the Brundtland Commission report) (U.N. WCED 1987). The report defined sustainable development as: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This report also defined strategic imperatives and preconditions for implementing sustainability and is considered a turning point in recognizing that sustainability needs to be addressed comprehensively, not with a piecemeal approach (Clayton and Radcliffe 1996). In general, sustainability emphasizes the integrated nature of human activities and the need to coordinate decisions among different sectors, groups, and jurisdictions. In transportation, sustainability is largely defined through impacts of the transportation system on the economy, environment, and general social well being. It is measured by system effectiveness and efficiency and the impacts of the system on the natural environment (Jeon and Amekudzi 2005).

Defining Sustainability for Transportation Agencies

Sustainable transportation can be seen as an expression of sustainable development in the transportation sector. While addressing "sustainable transportation" as opposed to "sustainability" is useful from the perspective of a transportation agency, it must be recognized that sustainability is defined by a broader agenda than transportation alone. It is necessary to balance this agenda with issues that are actually relevant to transportation agencies, especially in terms of what agencies have control/jurisdiction over.

Recent studies of state DOTs in the United States indicate that while sustainability is not explicitly mentioned in the mission and vision statements of most agencies, most of them touch on sustainability concerns by addressing issues such as the environment, future needs, and social equity (Jeon and Amekudzi 2005; UW 2007). Thus, it is clear that state-level transportation agencies in the United States are giving importance to sustainability issues. However, in those and similar agencies in the United States, the focus is more on environmental impacts than sustainability as a whole. Thus, a clearer understanding of sustainability principles and their relation to transportation agency functions is useful.

For example, Zietsman and Rilett (2002) discussed the principles of sustainable development that are relevant and need to be addressed from a transportation perspective.

- Intergenerational equity—Sustainable development wants to ensure that current and future generations can enjoy an acceptable quality of life. There should also be an equitable distribution of resources between and among communities and generations.
- Multidimensional—The three dimensions of sustainable development—social equity, economic development, and environmental stewardship—are interrelated and must be simultaneously addressed to meet the needs of current and future generations.
- Dynamic—In considering intergenerational equity, it is necessary to adapt to the changing needs of societies and generations over time.
- Continuum—Sustainability is not represented by discrete indications of sustainability or nonsustainability but as a continuum representing various degrees of sustainability.

These basic guiding principles of sustainability and sustainable transportation were taken into account while developing the performance-measurement framework and evaluation methodology for this research.

Performance Measurement for Sustainable Transportation

Performance measurement originated as a management tool used by private-sector organizations to evaluate progress toward goals using measurable results or targets (NCHRP 2003a). Performance indicators and performance measures refer to variables that help assess progress. Performance measures are broadly used for simplification, quantification, and communication. They translate data and statistics into succinct information that is readily understood, and used by people of widely different backgrounds including engineers, administrators, politicians, and the general public. Performance measures are typically aligned with strategic goals and objectives to ensure that these goals and objectives are met.

Traditionally the focus on performance measurement in transportation has been on the more operational and quantifiable objectives (transportation system perspective) as opposed to the broad encompassing nature of sustainability (which also includes qualitative measures). For example, 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 the areas of highway maintenance, safety, highway construction, public transit, and aviation (Poister 1997). However, the research suggested that performance measurement should undergo a paradigm shift to encompass measures of mobility, livability, accessibility, and sustainability.

Measures for sustainability require that system measures be integrated with environmental, social, and economic measures to ensure that all the aspects of sustainability are addressed. There has been a significant amount of published research during the past decade relating to transportation sustainability and sustainable transportation performance measures. Jeon and Amekudzi (2005), Litman (2009), Gudmundsson (2000), Hall (2006), and Zietsman et al. (2003) provide examples of indicators for sustainable transportation and compilations of sustainable transportation indicators used worldwide. Many of the example indicators discussed in these sources contain sustainability measures relevant at a national, regional, or system wide level, for example, per-capita exposure to environmental and safety impacts, employment and economic activity, system efficiency, levels of congestion and the use of alternative modes. Jeon (2007) also developed sustainability indicators relevant at a metropolitan-area level, which included environmental, economic, social, and system effectiveness dimensions. Additionally, there are many performance measurement–based sustainability rating systems developed in the civil engineering sector, focusing more on sustainability for construction and maintenance activities. Transportation-related examples include the Greenroads rating system (Muench et al. 2010) and the GreenLITES programs by the New York State Department of Transportation (NYSDOT 2010). These and other rating systems are modeled on the Leadership in Energy and Environmental Design (LEED) certification program, developed for building design by the United States Green Building Council (USGBC 2010). Although these rating system and performance measure examples are not directly relevant to the corridor-level transportation measures discussed in this paper, a review of them is useful to gain an understanding of the various applications of sustainability in different facets of transportation and civil engineering.

Requirements of a Good Performance-Measurement System

The identification of appropriate performance measures is a very important task because poor performance measures can lead to poor decisions and poor outcomes. Performance measures should be aligned with the agency's strategic goals and objectives. Typically, only one or two measures should be identified per objective (Zietsman and Rilett 2002). Because different groups, such as the general public, engineers, managers, and decision makers, have different expectations, needs, and technical expertise, it is very important to develop performance measures that are understood by a broad audience.

Collected data and relevant equations are used to quantify performance measures. Typical constraints for quantifying performance measures for sustainable transportation include aspects such as the cost and difficulty of obtaining the data and the political sensitivities related to certain performance measures. Aggregating and weighting the quantified performance measures produces composite measures, known as indexes, which provide a simplified representation of the underlying performance measures (Lomax et al. 1997).

Quantified performance measures, goals, and objectives support the decision-making process with regard to system performance, project selection, impact assessment, and agency or program performance (Poister 2005). The functions of performance measures in support of these areas can be categorized as (NCHRP 2003b)

- Internal communication (within divisions and districts as well as with top management),
- Business management (direct management activities),
- Decision support (support broad range of decisions, such as planning, budgetary), and
- External communication (with broad range of stakeholders including the public).

This research focuses on the development of a user-friendly "value planning" or "sustainability enhancement" tool. The emphasis, therefore, is on impact assessment, and the analysis tool addresses all four of the preceding functions.

Application of Multicriteria Decision Making

There are many approaches to decision making in the transportation planning context. Single-objective decision-making techniques, such as a benefit-cost analysis, convert all aspects into monetary values. Such methods are not adequate to deal with the complexities and intangible aspects associated with sustainable transportation, and thus multicriteria decision-making (MCDM) is a suitable alternative to deal with the comprehensive evaluation of multiple performance measures. Specifically relating to sustainability and transportation, Jeon (2007) provides a detailed discussion of the advantages of an MCDM approach, which are supported by the findings of Zietsman and Rilett (2002).

MCDM creates a means for translating qualitative attributes into a framework that can enable choosing between various alternatives in a scientific manner. The advantage of MCDM is its ability to account for a wide range of differing yet relevant criteria or objectives. Even if these criteria cannot be expressed in monetary terms, as is the case with externalities, comparisons can still be based on relative priorities (Nijkamp and van Delft 1977). The most commonly used MCDM methods include the multiattribute utility theory (MAUT), analytical hierarchy process, and outranking method (Olson 1996). For this application the MAUT approach was selected because it is a simple and intuitive approach to decision making. The MAUT approach is summarized in the following steps (Olson 1996):

Step 1: Identifythe various criteria and subcriteria to be used in the evaluation process.

Step 2: Rank the different criteria and subcriteria in order of importance.

Step 3: Rate the different criteria and subcriteria on a scale from 0 to 1, while reflecting the ratio of relative importance of one criterion over the next.
Step 4: Normalize these weights on a scale from 0 to 1.
Step 5: Determine criteria values for each alternative by using single-attribute utility functions on linear normalized scales.
Step 6: Calculate the utilities for the alternatives by obtaining the weighted linear sum for the criteria.

This research proposed a MAUT-based methodology that would evaluate individual performance measures and combine them into a final sustainability index value. The results from this analysis could be used in the sustainability evaluation process for a highway corridor or to compare results from different alternate scenarios.

Performance Measurement Framework

This section presents the approach and methodology used to develop a performance-measurement framework that linked its indicators to the goals of TxDOT's strategic plan. TxDOT's strategic plan for 2009–2013 (TxDOT 2009) is a document outlining the mission, vision, and goals for the entire agency. Five specific goals are identified and discussed in the strategic plan:

- Reduce congestion,
- Enhance safety,
- Expand economic opportunity,
- Improve air quality, and
- Preserve the value of transportation assets.

These five goals address the three dimensions of sustainable transportation: economic development, environmental stewardship, and social equity, to a certain extent. The main challenge in this project was to develop a set of performance indicators that reflected sustainability concerns within the scope of the strategic plan. The development of the performance indicators was done through a workshop process described in the next section. A key part of this process is the development of objectives termed *sustainability-related objectives* as an intermediate step in the development of performance measures. These were developed for each of the five goals in the strategic plan and helped define how sustainability is incorporated, while simultaneously addressing the strategic goals.

Following this, performance indicators were defined for each objective. These were then quantified as performance measures and implemented through the application of the MAUT decision-making methodology. Fig. 1 shows the conceptual framework of the entire process of translating goals into objectives and indicators, and the further steps of quantifying and evaluating

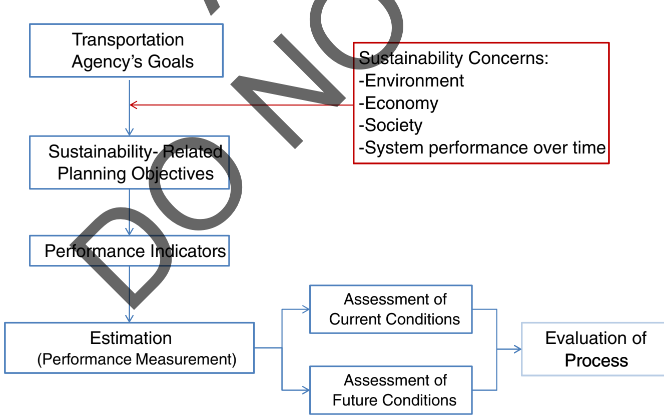

Fig. 1. Framework for sustainability evaluation

the performance measures. Evaluation of the indicators for both current and future conditions provides a true view of sustainability. The next section of this paper details how the sustainability objectives and performance indicators were developed and implemented through this framework.

Sustainability Objectives and Performance Measures

A workshop held with key TxDOT personnel facilitated development of sustainability objectives and performance measures related to TxDOT's strategic plan goals. Participants represented 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 apply to progress toward the goals. A working definition of sustainability agreed on for the specific context was developed: the provision of safe, effective, and efficient access and mobility into the future while considering the economic, social, and environmental needs of society. Workshop participants and facilitators used this definition as guidance in the development of the objectives and indicator sets, which were then further refined by the research team.

Initially, to facilitate ideas and discussion, the five goals were classified under the most appropriate sustainability dimension: environmental, economic, or social. Following this, a set of objectives (reflecting sustainability concerns) was defined for each of the strategic goals, and each objective was linked to a measurable indicator that could be used in the sustainability evaluation.

The scope of the indicators, as discussed in the "Introduction" section, was reiterated to the workshop participants. The measures and methodology developed were focused on the following elements:

- Planning level—The purpose of the project was to develop a sustainability enhancement tool to be used at the planning level as opposed to operational or design levels.
- Sustainable transportation—Although a broad range of performance measures was investigated, the focus of the project remained on addressing goals related to sustainable transportation.
- Corridor level—The focus of the study was at the level of a transportation corridor as opposed to project, network, or regional levels.
- Highway mode—The focus of the study was on the highway mode (road network with the vehicles, including transit vehicles, operating on them) as opposed to rail, aviation, or marine. Although the focus was on the highway mode, the methodology accounts for (and appropriately credits) approaches such as transit, innovative financing and land-use policies. These aspects are accounted for in the performance measures and in the methodology by which they are quantified and evaluated.

Table 1 summarizes the objectives and performance indicators developed for each of the goals through the workshop process. These indicators, when appropriately quantified and benchmarked, become performance measures that can be incorporated into the multicriteria assessment methodology. Most of these objectives and indicators address more than one aspect of sustainability. Therefore, rather than classifying each objective based on the facet of sustainability that it addresses, the remainder of this section presents a comprehensive discussion for each goal in terms of the motivation for selecting the objectives and how they relate to the different aspects of sustainability. The process of defining performance indicators for each objective is also presented.

Table 1. Objectives and Performance Indicators Developed

TxDOT goal	Sustainability-related objective	Performance measure
1. Reduce congestion	Improve mobility on highways	Travel-time index
	Improve reliability of highway travel	Buffer index
2. Enhance safety	Reduce crash rates and crash risk	Annual severe crashes per mile
	Improve traffic incident detection and response	Percentage lane-miles under traffic monitoring/surveillance
3. Expand economic opportunity	Optimize land-use mix for development potential	Land-use balance
	Improve road-based freight movement	Truck throughput efficiency
4. Preserve the value of transportation assets	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 nontraditional funding sources for highways	Cost recovery from alternative sources
	Increase use of alternatives to single-occupant automobile travel	Proportion of non-single-occupant travel
5. Improve air quality	Reduce adverse human health impacts and comply with ambient air quality standards	Air quality index
	Reduce greenhouse gas emissions	Daily CO_2 emissions

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 saving time and lowering emissions and fuel consumption, as well as safety. While a partial solution to congestion is to add highway capacity, political and institutional realities in the recent past have shown that this is not a practical solution. Congestion management and mitigation are significant from a system effectiveness standpoint, especially when comparing alternative scenarios or considering future increases in traffic.

Thus, maintaining or improving levels of congestion over time is desirable, as it can indicate reduced vehicle-miles traveled (VMT) and a reduced requirement for highway capacity expansions. The objectives and indicators for this goal cover the two aspects that are generally considered when referring to traffic congestion. The first addresses the actual travel-time increases caused by congestion, and the second examines how it affects the reliability of travel assessed over a longer time frame. Both of the selected indicators are used for congestion monitoring in the Texas Transportation Institute's (TTI's) 2007 Urban Mobility Report (TTI 2007).

Travel-Time Index

The travel-time index is a measure that indicates the extent of delays in travel caused by traffic congestion alone. It is generally quantified as the ratio between 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, empirical relationships are derived between the travel-time index and buffer index that can be used to estimate buffer index values.

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, and the second relates to having surveillance systems in place for monitoring traffic and incident response. Achieving these objectives has significant benefits in human lives saved and the economic costs of crashes.

Annual Severe Crashes per Mile

Crashes are most commonly expressed as a crash rate (the number of crashes per million VMT), 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* (Bonneson et al. 2006).

Percentage Lane-Miles under Surveillance

The percentage lane-miles under surveillance measure estimates the presence of surveillance facilities, including traffic monitoring and emergency response facilities, in coverage of a highway section by a traffic monitoring center. This coverage is expressed as a percentage of the total lane-miles. Having facilities such as traffic surveillance and incident response is beneficial from a safety perspective. These facilities can also aid congestion monitoring and emergency evacuations.

Goal 3: Expand Economic Opportunity

In TxDOT's strategic plan, this goal addresses trade opportunity, freight movement, faster deliveries, and the means of 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 defined objectives. Another aspect of job and business vitality is freight movement, which is also addressed as an objective.

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, as proposed by Cervero and Kockelman (1997). It is formulated to have the highest value when all categories of land use are equally distributed and the lowest values when all 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 with 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 this analysis. 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 nonhomogeneity 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 travel speeds on the links. Freight movement is a key economic benefit of highways, and the objective in this analysis was to maximize freight throughput without affecting highway performance. The theory behind this measure is that the impact of the economic benefits of trucks should be measured in a way that accounts for possible reductions in travel speeds attributable 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, was proposed.

Goal 4: Preserve 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 the 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 nontraditional funding sources for highways can help free state funds to promote other modes of transportation. When alternative funding encompasses toll roads, it could indicate that a greater portion of true user costs is being paid by automobile users themselves (Litman 2000). 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 actual costs and impacts of the land acquisition and construction. The final objective deals with the provision of mobility options other than single-occupant vehicle (SOV) automobile travel.

Average Pavement Condition Score

TxDOT monitors the condition of pavements in the road network by considering factors such as surface distress, rutting, and ride quality. The data for the entire network are collected in a pavement management information system (PMIS), which combines these factors into a pavement condition score expressed on a scale from 0 to 100. This condition score was 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 an 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. Although the impact of increased traffic because of 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 previously discussed. 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 previously discussed. It evaluates the higher occupancies achieved by carpooling, use of bus transit, or travel on 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 in urban areas. The United States Environmental Protection Agency (USEPA) has set standards for air quality, termed the National Ambient Air Quality Standards (NAAQS). The regulation of motor vehicle emissions is essential for adhering to these standards. While evaluating air quality alone does not address the whole range of environmental issues associated with road transportation, motor vehicle emissions are considered the most significant contributor for an existing highway. The impacts of emissions 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), volatile organic compounds (VOCs), and particulate matter (PM) 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, causes respiratory problems for humans. Since the NAAQS factor in the presence of these toxic pollutants, compliance with these standards is also included in the objective.

Though the state of Texas does not ordinarily consider carbon dioxide (CO_2) emissions 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.

Air Quality Index

This measure has three components: ozone, CO, and PM, each of which are assigned importance factors that add up to 100%. The default importance factors for each component are adjusted upward or downward, depending on the nonattainment status of the region such that increased importance is given to specific nonattainment components for the area. The emissions for the following pollutants are estimated: VOC, NO_x, CO, and PM. These are the pollutants generally taken into account in terms of human health impacts.

The rate of emissions for a vehicle depends on the operating speed and varies by vehicle type. These rates can be obtained from emissions estimation models (MOBILE6.2, the EPA model, is used in this research). VOC and NO_x are combined and expressed as NO_x equivalents and considered together for the ozone component. These individual emissions are each compared to predefined best-case and worst-case values and expressed on a 0 to 1 scale using linear interpolation. The individual component scores are then combined on the basis of the importance factors to obtain the air quality index value on a 0 to 1 scale.

Daily CO_2 Emissions

CO_2 is a gas emitted from burning fossil fuels and is associated with global warming. Vehicular emissions are a significant anthropogenic source of CO_2, and these must be considered when assessing the sustainability of transportation systems. The emissions rates for CO_2 in MOBILE6.2 were supplemented with emissions data from PEMS testing results that the authors obtained from their own research and used to quantify this measure. As in the previous measure, the quantified measure is expressed as the daily emissions of CO_2 in grams per mile of roadway.

Remarks on Selected Performance Indicators

It can be argued that the consideration of measures related to highways only, without consideration of other modes, is in itself antithetical to certain aspects of sustainability. Although this indicator set does not explicitly consider alternatives to automobile use, the performance indicators/measures have been structured such that an excess of VMT is penalized, and appropriate measures are calculated per lane-mile of infrastructure rather than per VMT. 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, the performance measures selected are adequate, without being impractical to evaluate.

Another aspect of sustainability captured in this research effort is the consideration of changes over time. Future and present conditions are evaluated on common grounds rather than by 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 provide a comprehensive listing of resources and indicator sets that relate to sustainable transportation. A review of those resources show that the indicator set proposed in this research provides a fairly complete view of issues that need to be addressed for sustainability.

Implementation of MAUT Evaluation Methodology

As previously discussed, the framework for a performance-based evaluation of highway sustainability has been developed to assess a single highway facility, termed a *section*. 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. 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 determination of how the measurement of each link compares with the average. This assessment can be used to compare different highways or different proposed projects for a single highway.

Quantification and Normalization of Performance Measures

The terms *performance indicator* and *performance measure* are loosely used as synonyms in this paper. If a distinction were to be made, it is that when sustainability indicators are quantified and benchmarked for a specific evaluation, they become performance measures. The sustainability indicators proposed are quantified as performance measures as the first step in the MAUT methodology. The data elements required to quantify each measure and the units in which they are expressed are summarized in Table 2. Based on assembled corridor data, the performance measures can be quantified for individual links and for the overall study section (corridor). For a particular analysis, each measure is evaluated for the existing conditions as well as for projected future scenarios. The measures are structured to allow for flexibility in data sources and for making assumptions in cases where data are not available. Data elements such as current and future traffic volumes can be obtained from travel demand models, corridor studies done by the DOT, or from recent traffic counts (with application of growth rates for future traffic). Land-use information can be obtained from parcel-based GIS data, from which future land development patterns can also be identified through the category designations. Data on transit ridership and frequency, truck volumes, pavement condition, etc., can be assembled from a variety of sources for current conditions, and reasonable assumptions made for future cases, if necessary. Further details on data sources and the quantification of measures are presented in Ramani et al. (2009).

Each of the performance measures needs certain benchmark values for comparison to indicate the specific performance measure's value (good or bad). This is expressed by scaling or normalizing the performance measure. To perform the scaling, however, it is necessary to define the 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. Each performance measure is then normalized (scaled) to be expressed on a 0 to 1 scale, where 0 corresponds to the worst-case scenario and 1 corresponds to the best-case scenario. This value is obtained through linear interpolation between the best and worst extremes and is termed as a *scaled performance measure value*. It is used to combine the results from the entire indicator set to a common basis. Further details on the calculation of the scaling extremes for the performance measures are presented in Ramani et al. (2009).

Allocation of Weights

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.

Table 2. 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 traffic monitoring/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	Average pavement condition score	Score from TxDOT's PMIS database	Dimensionless
4b	Capacity addition within available right-of-way	Number of lanes that can be added to a link within available ROW	Number of lanes
4c	Cost recovery from alternative sources	Project capital costs and sources; annual operating and maintenance costs and sources	Dimensionless
4d	Proportion of non-single-occupant travel	ADT; general-purpose lane occupancy; high-occupancy vehicle lanes and usage; details of bus and rail service	Percentage of total PMT
5a	Air quality index	Area's classification for NAAQS eight-hour ozone, CO, and PM standards; emissions rates for NO_x, CO, PM and VOC (emissions model); peak and off-peak volumes; operating speeds	Dimensionless
5b	Daily CO_2 emissions	Emissions rates for CO_2; peak and off-peak volumes; operating speeds	Grams per mile per day

The weights for individual measures are allocated such that they add to 1, and measures that are deemed more important are given a higher weight. Two sets of weights are used: 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 (measure-weights). This enables calculation of a goalwise performance to evaluate those goals that are being sufficiently addressed from a sustainability perspective and those that require further improvement. The set of goal-weights then define the relative importance assigned to TxDOT's five goals, and the aggregate indicators for each goal can be combined into a final sustainability evaluation index.

The allocation of weights can be a controversial aspect because of its subjectivity and possible impact on the final results. It was decided that while applying the methodology, TxDOT practitioners at the district level can choose to develop their own weights or use default weights developed by the Transportation Planning and Programming Division of TxDOT. The development of these default weights was conducted through a Delphi process in a workshop setting. Participants ranked the different elements in order of importance and then rated the different elements on a scale from 0 to 1, while reflecting the ratio of relative importance of one element over the next. Participants then discussed why they ranked specific elements highest and lowest. After this, the group adjusted scores and developed averages for the various elements. In this manner, two sets of default/recommended weights were defined (a set of goal-weights and measure-weights for rural areas and another set of each for urban areas). These default weights may be applied based on the location of the study corridor or replaced on a case-specific basis, if required.

User-Friendly Analysis Tool

A user-friendly analysis tool was developed in the form of a Microsoft Excel calculator to carry out the entire performance measurement and MAUT process for a corridor. The tool can quantify the selected performance measures and calculate the final sustainability index values. It was developed so that users can select the default weights, or enter their own weights and turn certain goals and performance measures on or off based on the specific project. The user is prompted to enter certain basic data into the data entry sheet. After the data have been entered, the calculator performs the calculations and determines the performance measure values and index values. The tool produces summary graphs and tables that can be used to evaluate the results. The analysis tool is ideal to perform sensitivity analyses and to make comparisons between alternatives, even over space and time. This calculator tool is used to carry out an analysis for a pilot corridor, the results for which are presented in the next section.

Pilot Application

Description of Test Bed

A 15-mile section of US-281 in San Antonio, Texas, was chosen as the study corridor. A map of this corridor is shown in Fig. 2. The sustainability evaluation was performed for this highway using the analysis tool. The study section on US-281 is entirely located in Bexar County, Texas. It runs from IH-410 in downtown San Antonio in the south to the Comal/Bexar county line in the north. The section from IH-410 to Loop 1604 (a distance of approximately 7 miles) is fully access-controlled, consisting of three lanes in each 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 2 miles and two lanes per direction beyond that point. Next to the San Antonio International Airport, the corridor is predominately dense commercial development. North of Loop 1604, the development becomes less dense, with pockets of commercial development (mainly retail). At the northern end of the

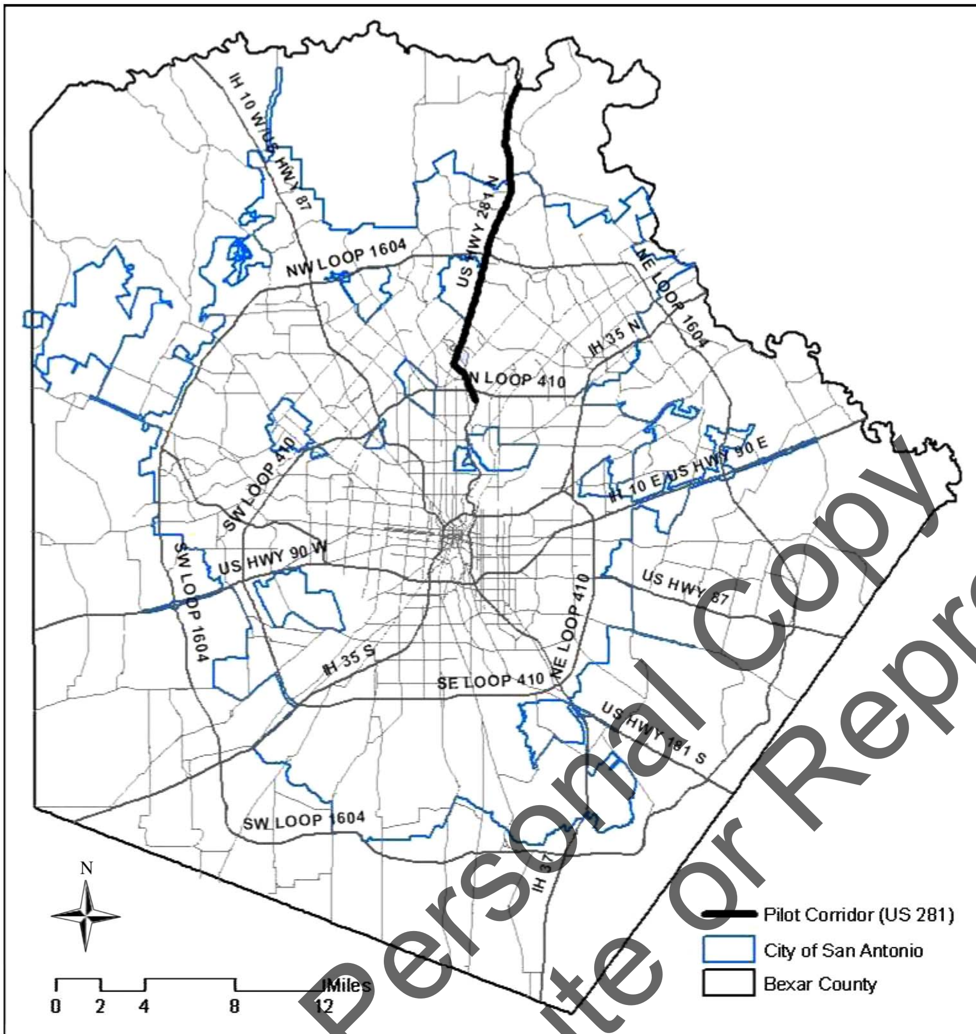

Fig. 2. Location of pilot corridor

corridor, at the Bexar/Comal county line, the development becomes sparser, with occasional lower density residential developments and small retail outlets.

The selected study section of US-281 is subdivided into four links for the analysis. Table 3 shows the beginning 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.

Three scenarios were used for analysis and comparison:

1. Base case. This scenario represents current conditions on the study section. The analysis results would provide an indication of the relative sustainability of the corridor as it currently operates.
2. Future Scenario 1 (no build). This scenario replicates the currently existing conditions, except for increased traffic volumes 20 years into the future. This would provide an indication of performance if the demand on the corridor continues to increase without any changes being made to the corridor conditions.
3. Future scenario 2 (additional measures). This scenario represents corridor conditions as projected 20 years into the future as well. However, in addition to the consideration of increased demand, lane expansions (two-lane sections made three lanes in each direction, as planned by TxDOT), added transit services, and other changed parameters were reflected in the analysis.

The base case comprises the existing corridor and uses data that are as close as possible to 2005 values. The future scenarios are based on projections for 2025.

Table 3. Link Details and Lengths for US-281 Case Study

Link	Start	End	Length (miles)
1	IH-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	IH-410 N	Comal County line	15.0

Results: Index Values with Disaggregate Illustration

One of the requirements for the analysis tool is that it should be based on data that are readily available at the regional or district level of an agency. Each of the performance measures were quantified for both the base case and the future scenarios, as well as for the summary graphs and tables produced by the analysis tool. For the three cases, index values were calculated for each of the links,

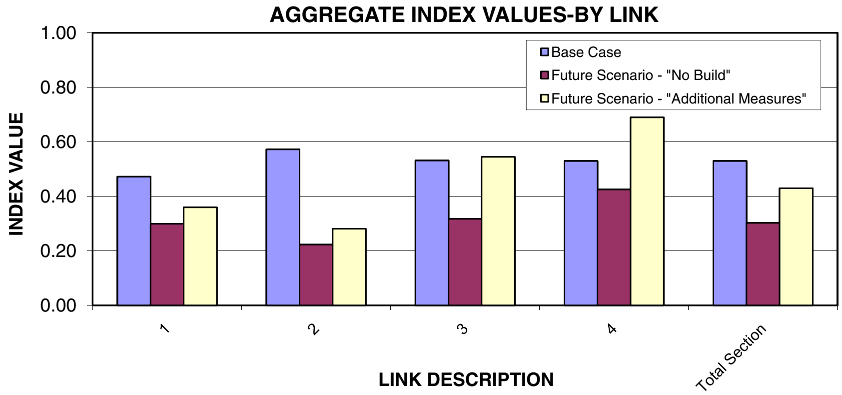

Fig. 3. Results—linkwise analysis

based on the normalized performance measure values and the default weights developed for this research. The combined index values and results for the entire section are also calculated. Similarly, index values for the entire section are provided for individual goals as well as for all the goals combined. This disaggregate approach makes it possible to identify specific sections of the corridor that need improvement. By providing goalwise index values, the results can also indicate which goals are not being addressed adequately from a sustainability perspective.

Fig. 3 shows the disaggregate (link) results for the pilot corridor. The figure shows that there is not much variation between the overall index values for the links. However, Link 1, which is closest to downtown San Antonio, has the lowest index values for the base case (i.e., current conditions). This is expected given the greater levels of congestion at this location. However, Link 2 experiences a much more significant drop in the overall index value in the future (for both the no-build and additional-measures scenarios), possibly because of expected increases in traffic volumes occurring farther north rather than near downtown San Antonio, where traffic volumes are already reaching levels of saturation.

Thus, while at the corridor level, the future scenarios both show a drop in the overall sustainability index value, the disaggregate application helps identify problem sections (where the reduction in performance is more significant) that need to be worked on from a sustainability perspective. Overall, it can be seen that Links 1 and 2 perform worse, especially in the future cases. However, the fact that they are located closer to the city center makes it easier to address the issue of sustainability by providing alternate transportation facilities or other strategies as future planning measures. The final two links have better sustainability indicator values for the future, which may be because the increase in volumes in the future may not have risen to an extent that adversely impacts safety, congestion, or environmental factors.

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 goalwise performance, the measure-weights are applied to individual measures within each goal. The default weights for urban cases provided in the analysis tool were used. The results for the goalwise analysis are shown in Fig. 4. The goal area experiencing the most significant reduction (worsening) in performance is the congestion goal, regardless of whether the roadway capacity is unchanged (no build) or increased (additional measures). The performance with respect to the safety goal, however, decreases significantly for the no-build scenario but increases if the additional measures are taken into consideration. The changes on the remaining three goals are not as drastic. An additional aspect is the performance with respect to the air quality goal. The future improvements are largely attributable to improved vehicular technologies that are reflected in reduced future-year emissions. The fact that the improvement on this goal is the same for both the no-build and additional-measures scenarios indicates that the improvement is not a function of any transportation-related measures undertaken on the corridor. The no-build scenario analysis is useful in this respect because it provides an indication of whether the measures undertaken as a part of the additional-measures scenario actually serve to improve the corridor's sustainability. For example, the fact that the performance for the congestion goal decreases sharply in the future for both scenarios

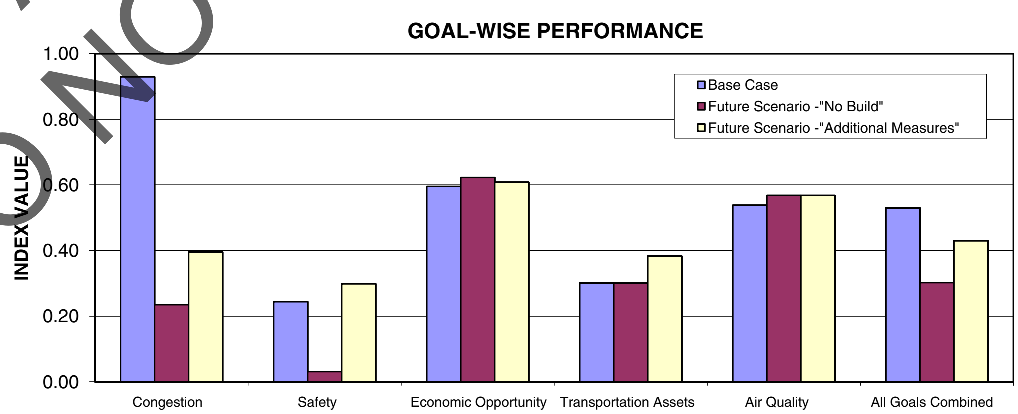

Fig. 4. Results—goalwise analysis

indicates that capacity addition is not a sustainable solution for this corridor. The increased demand needs to be tackled through other means, for example, promoting transit, or taking measures to reduce travel demand.

Thus, from a sustainability perspective, the most damaging factor in the future-case scenario is the increase in traffic volumes that affects congestion, safety, and greenhouse gas emissions. However, there is some mitigation of these impacts in the additional-measures scenario because of technological advancements that reduce vehicular emissions and small measures such as the expansion of surveillance facilities. The importance of adding more transit facilities, leveraging alternative funding, and engaging in asset management is highlighted in the results. However, the bottom-line issue remains that the increases in demand on the corridor are most likely unsustainable in the future. Thus, for the case study corridor, links that performed worse than average are identified. Goalwise progress was assessed to determine which goals were not being met and to help identify how to achieve them in a sustainable manner.

Additional Analysis—Impact of Weights

The index values and results provided in the previous sections used the set of default weights developed through the Delphi process and conducted with TxDOT staff. These weights therefore reflect the relative priorities of the staff group. For example, among the goals, the safety goal was weighted the highest. As previously mentioned, the issue of weight allocation is controversial because the assignment of weights can be used to affect outcomes in this type of MAUT analysis.

As an additional analysis to gauge the impact of weight allocation, the results of the analysis were compared with the results obtained when all goals were given equal weight, and all measures corresponding to a particular goal were also given equal weight. The differences in index values for the TxDOT-assigned-weights and equal-weights scenarios were compared, as shown in Table 4.

As seen from the table, the index values differ only by a few percentage points from when equal weights are assigned to when the weights assigned by TxDOT staff were used. While these findings are not a substitute for a detailed sensitivity analysis for the goals/weights, they provide a preliminary indication that the weight allocation will not necessarily overturn the results of the methodology.

Conclusions and Scope for Future Work

This paper discusses the findings from research conducted to develop a methodology and tool for state transportation agencies to evaluate sustainability as a part of the highway-corridor planning process. The research was applied to the TxDOT as an illustrative study. A framework of performance measures linked to TxDOT's goals was developed, and an MAUT methodology was used to quantify and evaluate the measures to obtain sustainability index values at the corridor and link levels. This methodology was implemented in the form of a user-friendly analysis tool, which is being introduced to transportation planning practitioners around the state of Texas through a series of interactive workshops.

However, there is scope for additional research that can further promote sustainability performance measurement for state-level transportation agencies. The following points discuss the scope for future research:

- This research provided a working definition of sustainable transportation: "The provision of safe, effective, and efficient access and mobility into the future while considering the economic, social, and environmental needs of society." However, it needs to be acknowledged that sustainability has a much broader scope and agenda. Although this work touches on various aspects of sustainability, it is desirable that future research builds on these findings to promote a more holistic view of transportation as it relates to other human activity.
- The scope of this research was restricted to the highway-corridor level and identified performance measures that could address the goals of TxDOT's strategic plan while accounting for sustainability concerns. This allowed for the methodology to be suitable for practical implementation. However, greater consideration of nonhighway modes and the development of a similar performance measurement-based analysis at the regional/network level can also be useful to future research.
- The set of 12 performance measures developed in this research are found to address sustainability fairly comprehensively. However, certain performance measures may not be as sensitive to changes at the corridor level as others. Further research on this issue can also serve to improve the performance-measurement approach to sustainability among transportation agencies.
- The processes of scaling and weighting are important in the application of the MAUT methodology for evaluating the set of performance measures. Further research on the impacts of weighting and scaling (in terms of a sensitivity analysis) and other approaches to the scaling and weighting process (for example, consideration of nonlinear scaling) could also prove useful, in addition to the exercise presented in this paper that assesses the impact of weighting on the overall results.

In conclusion, the findings from this research show how concepts of sustainability can be applied for practical implementation at the transportation planning level. It can be seen as a first step, not only for TxDOT and similar state agencies to consider sustainability, but also to educate agencies about a broader view of sustainability. The methodology made it possible to identify the specific performance measures that need improvement or specific areas in the corridor that are of concern. It is intuitive, based on readily available data, and is easy to apply. It is a valuable practitioner tool for state transportation agencies to assess the relative sustainability of their transportation corridors now and in the future. It allows for

Table 4. Comparison of Index Values for Application of Different Weights

Link	Index values for TxDOT-assigned weights			Index values for equal weights		
	Base case	Future 1	Future 2	Base case	Future 1	Future 2
1	0.47	0.30	0.36	0.45	0.29	0.39
2	0.57	0.22	0.28	0.51	0.24	0.34
3	0.53	0.32	0.54	0.56	0.36	0.49
4	0.53	0.42	0.69	0.55	0.45	0.61
Total section	0.53	0.30	0.43	0.52	0.33	0.44

comparisons within a corridor and with other corridors and identifies the improvements needed to progress toward sustainability.

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