Evaluating Plan Alternatives for Transportation System Sustainability: Atlanta Metropolitan Region

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ABSTRACT
A growing number of agencies have begun to define “sustainability” for transportation systems and are attempting to incorporate the concept into the regional transportation planning process. Still, very few metropolitan planning organizations (MPOs) capture the comprehensive impact of transportation system and land use changes on the economy, environment, and social quality of life, which are commonly considered the essential three dimensions of sustainable transportation systems. This paper demonstrates an application of the Multiple Criteria Decision Making (MCDM) approach for evaluating selected transportation and land use plans in the Atlanta region using multiple sustainability parameters. A composite sustainability index is introduced as a decision support tool for transportation policymaking, where the sustainability index considers multidimensional conflicting criteria in the transportation planning process. The proposed framework should help decision-makers with incorporating sustainability considerations into transportation planning as well as identifying the most sustainable (or least unsustainable) plan for predetermined objectives.

Key Words: decision making, performance measure, sustainable development, sustainable transportation, transportation planning

1. INTRODUCTION
A growing number of agencies have begun to define “sustainability” for transportation systems and take steps to incorporate the concept into the regional...
transportation planning process. The most widely used definition of sustainable development, from the Brundtland Commission, is the basis of most definitions of sustainable development in various disciplines: development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). A literature review indicates that operational definitions of sustainable transportation systems should at least capture attributes of system effectiveness and system impacts on economic development, environmental integrity, and the social quality of life (See Figure 1). The Canadian Center for Sustainable Transportation, for example, has defined a sustainable transportation system as one that (1) allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations, (2) is affordable, operates efficiently, offers choice of transportation mode, and supports a vibrant economy, and (3) limits emissions and wasting within the planet ability to absorb them, minimizes consumption of non-renewable resources, reuses and recycles its components, and minimizes the use of land and production of noise.

Considering a broader definition of transportation sustainability as improving the overall quality of life not just enhancing transportation systems, mission statements of about 40 percent of the State Departments of Transportation (DOTs) in the United States now include elements of sustainability. However, very few metropolitan planning organizations (MPOs) in the United States attempt to evaluate a broader impact of transportation system and land use changes on the economy, environment, and social quality of life, which are often considered the essential dimensions of sustainability. Conventional evaluation of transportation plans has focused largely on performance measures pertaining to transportation system effectiveness (i.e., congestion and vehicle miles traveled) as well as air quality impacts of the system.

Figure 1. Three essential factors of transportation system sustainability.
The objective of this study is to demonstrate an application of an integrated framework for incorporating sustainability considerations in transportation planning and decision-making. First, this paper discusses current practices in transportation system sustainability with an overview of methodologies being applied for sustainability evaluation. Second, the study identifies a broad range of sustainability measures and applies these measures to evaluate competing transportation and land use plans. The evaluation is conducted to characterize the anticipated relative contributions of the plans to regional sustainability of Metropolitan Atlanta. Third, the study proposes a decision support tool using a Multiple Criteria Decision Making method to synthesize the sustainability assessment results and help identify superior or dominant plans, and tradeoffs among competing plans with no clearly dominant alternative. The proposed framework should help decision-makers with incorporating sustainability considerations into transportation planning.

LITERATURE REVIEW

Sustainability Indicator Frameworks

A comprehensive literature review was conducted on sustainability indicators from sixteen different initiatives around the world, including North America, Europe, Australia, and New Zealand (Jeon and Amekudzi 2005). The review indicated that while a standard framework for evaluating progress toward sustainability did not exist, similar to the existing definitions of transportation sustainability, there are common themes and dimensions. Most of sustainability indicators in the literature have been defined using frameworks that may be categorized as: (1) linkages-based frameworks, (2) impacts-based frameworks, and (3) influence-oriented frameworks. The existing and emerging evaluation frameworks attempt to capture at least one of the following: (1) the causal relationships that lead to progress toward or deviation away from sustainability, (2) the impacts of decisions on the three important areas that define sustainability, i.e., the economy, environment, and social well-being or quality of life, and (3) the level of influence or control that the responsible agencies have over the causal factors of sustainability. The review also provided an extensive list of indicators sorted by the relative frequencies with which they appeared in the sixteen initiatives. All the transportation sustainability indicators reviewed may be classified into the following four major categories: transportation system effectiveness-related, economic, environmental, and socio-cultural/equity-related indicators. The present status of addressing sustainability in transportation planning and provision seemed to indicate a higher focus on the effectiveness of transportation systems as well as the resulting environmental impacts (mainly air quality impacts), and less of a focus on economic and social impacts.

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

Zegras (2006) presents the Sustainability Indicator Prism that represents the hierarchy of goals, indexes, indicators, and raw data as well as the structure of multidimensional performance measures (Zegras 2006). In the four-layered pyramid, the top of the pyramid represents the community goals and vision, the second layer represents a number of composite indexes around the selected themes, and the third layer represents indicators or performance measures building from raw data at the bottom of the pyramid. This concept can also be considered as the combination of Hart’s category or issue lists (environmental, economic, and social aspects) and goal-indicator matrix, which organizes indicators/indexes around a set of community goals or various sustainability issues. This framework is particularly useful in helping decision-makers to clarify community goals for sustainability around the essential dimensions of sustainability (environmental, economic, and social dimensions, etc.), and indicators and composite indexes are constructed based on the categorized goals and objectives.

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

Multiple Criteria Decision-Making in Transportation

A review of analytical methods for sustainability evaluation reveals that while there is no standard method, most models are based on the multidimensional themes of economic, environmental, and social impacts. Such a multidimensional nature of sustainability indicates that multicriteria or multiobjective methods would be more appropriate for sustainability assessments than single-criterion/single-objective methods.

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

MCDM methods are widely diverse. Chen and Hwang (1991) classified a group of MCDM methods according to the type of information and the salient features of information received from the decision maker. The weighted sum model (WSM), the weighted product model (WPM), and the analytic hierarchy process (AHP) method are the most commonly used MCDM methods. This study employs the weighted sum model (WSM) that has various strengths over the other methods. This model is particularly simple, it is well-known, its technical parameters have a clear and explicable substantive interpretation, it allows processing of the difficult problem of the relative importance of criteria in a precise way, and it permits avoidance of the difficulties that are inherent in every ordinal aggregation (Bana e Costa 2003).

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

The literature indicates that MCDM methods have often been applied to project-level studies since the early 1980s. MCDM applications to broader scope analyses, such as the evaluation of transportation plans or policies, are more recent research trends that seem to have been propagated in the literature since 2003. One of the most common methodologies of MCDM is Saaty’s Analytic Hierarchy Process (AHP) developed in 1970s to provide a systematic approach to setting priorities and decision-making based on pairwise comparisons between criteria (Saaty 1995). Since Saaty introduced the application of this method in transportation decision-making, the AHP method has frequently been used to incorporate multiple decision criteria in the evaluation of transportation alternatives.
(Tabucanon and Lee 1995; Latuso and Toivanen 1999). Another recent trend includes applications of different types of “fuzzy” multicriteria decision-making approaches (Aboul-Ela et al. 1982; Karsak and Ahiska 2005; Lee and Chou 2006; Bell 2006; Filippo et al. 2007). These fuzzy-type MCDM methods attempt to cater for uncertainty, vagueness, or fuzziness commonly inherent in human decision-making due to a lack of information or constraints in human thinking. Other initiatives combine the AHP method with different types of fuzzy MCDM methods. MCDM applications to broader scope analyses such as the evaluation of transportation plans or policies are also increasingly prevalent. The next section discusses an application of MCDM to planning at the metropolitan level using data from the Atlanta Metropolitan Area. Interim work on this study was presented at the 2007 Annual Transportation Research Board Meeting (Jeon et al. 2007).

3. INCORPORATING SUSTAINABILITY CONSIDERATIONS INTO THE REGIONAL PLANNING PROCESS

3.1. Overview of the Methodology

One way in which sustainability considerations can be considered effectively in regional transportation planning is by applying the following: (1) identifying pertinent sustainability issues and regional sustainability goals for the metropolitan region of interest, (2) defining relevant performance measures for transportation system sustainability based on the predetermined issues and goals, (3) analyzing and quantifying the sustainability impacts of alternative transportation and land use scenarios developed for the region, (4) constructing a Composite Sustainability Index (CSI) using the Multiple Criteria Decision Making (MCDM) theory, and (5) visualizing the sustainability indexes using a decision support tool in order to identify the most sustainable (or least unsustainable) plan for predetermined sustainability-oriented objectives.

The core element of this framework is the Composite Sustainability Index (CSI) tool combined with the multiple criteria decision making (MCDM) method. Considering the essential dimensions of a sustainable transportation system as system effectiveness, environmental, economic, and socio-cultural sustainability, the following profile graph can be used as a practical decision support tool (See Figure 2). A full diamond shape is considered to be the maximum achievable level of sustainability for scenarios evaluated based on the current sustainability goals and objectives for the region. The area of each diamond conveys the relative level of sustainability. Using the visual index tool, decision-makers can identify clearly superior alternatives but also consider tradeoffs that multiple scenarios present relative to the different sustainability dimensions.

3.2. Pertinent Sustainability Issues and Regional Goals

The case used in this study draws from qualitative data on regional goals, objectives, and performance measures and quantitative data supporting three transportation and land use scenarios from the Atlanta metropolitan region. Figure 3 illustrates the analysis area encompassing 13 counties and 1,683 traffic analysis zones (TAZ) in metro Atlanta. The mission of Georgia Department of
Transportation (DOT) is to provide a safe, seamless, and sustainable transportation system that supports Georgia’s economy and is sensitive to its citizens and environment. Among the DOT mission statements reviewed in 2005, Georgia’s mission statement turned out to be the only one that explicitly incorporated the

Figure 2. Visual Composite Sustainability Index Tool.

Figure 3. Atlanta metropolitan 13-county region.
The Atlanta Metropolitan Area is the ninth-largest metropolitan area in the United States. More than half of the state’s 4.7 million population lives in the metro area and it will continue to grow to a population of 6 million and employment of 3.3 million by the year 2030 (Atlanta Regional Commission (ARC) 2006). Atlanta is arguably a poster-child for cities worldwide experiencing rapid urban sprawl, population growth, and commercial development.

Limited transit options and high automobile dependency are considered intertwined problems in the region, as evidenced by automobile share at 92% of total home-based work trips (ARC 2004a). Metro Atlanta faces severe congestion, with the associated air quality and respiratory health issues. Roadway congestion and traffic delay have been estimated to cost Metro Atlanta residents 101 million person-hours of delay every year, equating to $2 billion dollars in total delay costs annually (Texas Transportation Institute (TTI) 2007). According to the Texas Transportation Institute, the travel time index (traffic delay and congestion costs) has increased over 26% in the past eight years and Metro Atlanta has the 11th most congested freeway system in the United States. As of 2005, the 13-county non-attainment area for the one-hour ozone standard, in place for the last 15 years, was also revoked. The Atlanta non-attainment area currently includes 20 counties with respect to a revised, stricter eight-hour ozone standard. Based on these sustainability issues, the long-range regional transportation plan, Mobility 2030, presented the following goals:

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

### 3.3. Relevant Sustainability Definitions and Performance Measures

Based on the regional goals and prior literature review, efforts to improve transportation system sustainability should incorporate attributes of system effectiveness and system impacts on the economic development, environmental integrity, and the social quality of life. Thus, these four dimensions are considered in the regional planning context. Transportation system effectiveness captures the concept of mobility, which is defined as fluidity of movement, and system performance for regional highways and transit systems. Environmental sustainability includes issues such as natural resource preservation, pollution prevention, and other factors influencing environmental integrity for current and future generations. Economic sustainability is defined as maximizing economic efficiency and affordability and promoting regional economic development by implementing certain transportation plans. Economic efficiency can be achieved by increasing user welfare benefits and decreasing total time spent in traffic. Social sustainability captures social equity, human health, safety and security, accessibility to basic services, and overall quality of life by implementing certain transportation plans.

Figure 4 conceptualizes the relationship among the four sustainability dimensions as well as the interactions among these dimensions and the outer policy sphere. These sustainability dimensions are considered to be connected by their common elements or drivers which simultaneously influence the multiple
sustainability dimensions. Meanwhile, these dimensions also interact with the outer policy or institutional sphere. The outer policy sphere includes various urban or metropolitan issues not under the direct control of transportation officials, e.g., population/employment growth, market forces, and other government policies. Transportation systems are influenced by and influence the outer organizational and institutional network of policymakers, firms, non-governmental organizations, and stakeholders that together comprise the broad policy system that acts upon the sustainability dimensions (Dodder et al. 2004).

Performance measures should be determined based on the regional goals and objectives in order to take into account all the issues identified as relevant. Table 1 shows these goals categorized into each dimension of sustainable transportation and the appropriate performance measures that address the different goals. It is noteworthy that transportation system effectiveness is added to the three basic dimensions of sustainability because transportation mobility and system performance are indispensable components of transportation system sustainability. Moreover, system effectiveness may often be considered a minimum criterion in that planners have regarded effectiveness as the starting point and other perspectives as optional, additional criteria. Decision-makers, however, should think about the sustainability impacts of selecting one plan over another in a much broader context. A broader set of measures is used in this study than in conventional transportation planning which has tended to focus on congestion, mobility, and minimal environmental concerns (air quality indicators generally). Each goal and objective is represented by one or more performance measures as shown in Table 1. Mobility, which is a component measure of the transportation
<table>
<thead>
<tr>
<th>Sustainability dimension</th>
<th>Goals and objectives</th>
<th>Performance measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation System Effectiveness</td>
<td>A1. Improve Mobility</td>
<td>A11. Freeway/arterial congestion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A12. Travel rate (minute/mile)</td>
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<td></td>
<td>A2. Improve System Performance</td>
<td>A21. Total vehicle-miles traveled</td>
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<td></td>
<td></td>
<td>A22. Freight ton-miles</td>
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<td></td>
<td></td>
<td>A23. Transit passenger miles traveled</td>
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<td></td>
<td></td>
<td>A24. Public transit share</td>
</tr>
<tr>
<td>Environmental Sustainability</td>
<td>B1. Minimize Greenhouse Effect</td>
<td>B11. CO₂ emissions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B12. Ozone emissions</td>
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<td></td>
<td></td>
<td>B22. CO emissions</td>
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<td></td>
<td></td>
<td>B23. NOₓ emissions</td>
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<tr>
<td></td>
<td>B4. Minimize Energy Use</td>
<td>B41. Fuel consumption</td>
</tr>
<tr>
<td></td>
<td>C2. Maximize Affordability</td>
<td>C12. Total time spent in traffic</td>
</tr>
<tr>
<td>Social Sustainability</td>
<td>D1. Maximize Equity</td>
<td>D11. Equity of welfare changes</td>
</tr>
<tr>
<td></td>
<td>D2. Improve Public Health</td>
<td>D12. Equity of exposure to emissions</td>
</tr>
<tr>
<td></td>
<td>D3. Increase Safety and Security</td>
<td>D13. Equity of exposure to noise</td>
</tr>
<tr>
<td></td>
<td>D4. Increase Accessibility</td>
<td>D21. Exposure to emissions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D22. Exposure to noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D31. Accidents per VMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D32. Crash disabilities</td>
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<tr>
<td></td>
<td></td>
<td>D33. Crash fatalities</td>
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<tr>
<td></td>
<td></td>
<td>D41. Access to activity centers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D42. Access to major services</td>
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<tr>
<td></td>
<td></td>
<td>D43. Access to open space</td>
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</table>

VMT: Vehicle miles traveled.
Effectiveness goal, is captured by average freeway speed, for example. Similarly, air pollution is represented by the emissions of two ozone precursors: volatile organic compounds (VOC) and oxides of nitrogen (NOx); economic efficiency by the time spent in traffic, and social equity by the relative levels of exposure to emissions from the transportation system.

3.3.1. Selected Sustainability Measures and their Evaluation

Transportation Effectiveness Indicators

Average freeway speed (A11) and vehicle miles traveled per capita (A21), the average distance each person in the region drives each day, are selected to represent transportation system effectiveness. Average freeway speed is used as a proxy for freeway congestion, so it may not fully represent the level of mobility despite its popularity. Mobility and system performance are considered to be better off when average freeway speed is higher and vehicle miles traveled per person is smaller, respectively. Not surprisingly, these two indicators are often found to be negatively correlated: average freeway speed would increase as vehicle miles traveled per capita decreases. In addition, average freeway speed may not fully represent the level of transportation effectiveness because different areas have different freeway configurations and O-D pairs served by freeway.

Environmental Sustainability Indicators

Daily emissions of volatile organic compounds (VOC) and oxides of nitrogen (NOx), two precursors of ozone, are selected to capture the level of environmental integrity resulting from different transportation plans. Mobile 6.2 emission rates for an analysis year, vehicle speed, and roadway type are adopted from the Conformity Determination Report developed by Atlanta Regional Commission (ARC) (ARC 2004b). A traditional link-based procedure enables daily emissions to be calculated for each link in the network by multiplying vehicle miles traveled by each emission rate, and then summing to obtain daily level across the entire region (Guensler et al. 2004). The level of environmental sustainability is considered to be better off when regional mobile source emissions are lower.

Economic Sustainability Indicators

Vehicle hours traveled per capita (C12), the average duration each person in the region drives each day, is chosen for an economic sustainability indicator. A transportation plan with fewer vehicle hours traveled per person is regarded as more efficient and economically sustainable plan. Other freight and modal measures would be useful for capturing economic sustainability.

Social Sustainability Indicators

Social equity can be captured by equity of exposure to emissions (D12), and public health is represented by exposed population to emission (D21). Actual exposure to pollutant concentrations is beyond the scope of the current analyses, due to the complex nature of predicting hourly pollutant concentrations and population movements for exposure assessment. However, as exposure models continue to evolve, this metric can be fully incorporated into the sustainability
metric. This study adopts several surrogate measures, which are highly simplified in some perspectives, but capture some of the core characteristics. As additional modeling tools are approved for regulatory analysis, they will extend the present capabilities of analysts.

*Equity of Exposure to VOC and NOx Emissions (D12).* The potential differential equity that may result from alternative transportation plans is evaluated using the equity of emission distribution over (1) the geography and (2) different income levels. The goal of these metrics is to assess the spatial distribution of pollutant concentrations relative to the home locations of various demographic/income groups for exposure to fine particulate matter and toxic air contaminants. First, the spatial equity indexes are developed by ordering 1,683 TAZs from highest to lowest emission density, which is calculated by dividing total emissions contained by land acre, then plotting the cumulative percentage of total land area against the cumulative percentage of pollutants (U.S. Federal Highway Administration (FHWA) 2006). The higher the index, the greater the spatial equity that can be achieved. Second, the income equity index quantifies the difference of share between four income levels and emission concentration for each income level. The percentage of households with low income (less than $20 K), low medium income ($20 K–$50 K), high medium income ($50 K–$100 K), and high income (more than $100 K) are individually applied for the specific analysis year (ARC 2004a). The income equity indexes are calculated from the following equation:

\[
\sum (X_i - Y_i)^2 \times 100
\]

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

*Exposure to VOC and NOx Emissions (D21).* These measures are designed to compare the coincidence or proximity of people to air pollutants such as VOC and NO\(_x\). As a surrogate for population exposure, population density by TAZ is multiplied by the daily average emissions density, then the values are summed across the entire region. Higher human impact indexes indicate that high population density and high pollution density are more likely to occur in the same proximity (FHWA 2006). The researchers acknowledge that the actual exposure is a much more complicated issue considering the complex nature of predicting hourly pollutant concentrations and population movements for exposure assessment. The averaging method (across a TAZ) used in the study, for example, will significantly underestimate local population exposures to fine particulate matter and toxic air contaminants, which are significantly elevated within 500 meters of a freeway (Guensler et al. 2004). Future work includes examining the feasibility of adapting alternative approaches to the assessment.

### 3.4. Selected Transportation and Land Use Scenarios

To address sustainability issues more effectively, transportation and land use interaction should be fully accounted for in the regional planning process. The Atlanta Regional Commission (ARC), the MPO of the Atlanta metropolitan...
region, appears to be in step with this trend and has launched Envision 6 program, which essentially integrates land use planning and transportation planning as it updates the Regional Transportation Plan (RTP). Envision 6 has been used in developing several integrated transportation and land use scenarios using the INDEX software based on a series of stakeholder meetings, regional charrettes with various stakeholders, and web and telephone surveys (ARC 2006). This study evaluates three different transportation and land use scenarios of the Atlanta Metropolitan Region: (1) the Baseline 2005 scenario, (2) the Mobility 2030 scenario, and (3) the Test Case 2030 scenario. The Mobility and Test Case scenarios are made up by integrating an adopted regional transportation plan for 2030 with ARC’s two land use scenarios, which are the Mobility 2030 and Local Aspirations scenarios. The transportation network for the Draft Local Aspirations scenario was unavailable during the analysis period, so the Mobility 2030 and the Test Case 2030 have identical transportation planning outcomes/forecasts but different land use patterns (i.e., distribution of population and employment). Thus, while the test case is useful for demonstrating the methodologies applied, the results of the analysis should be taken in the context of the limitation introduced by using the same transportation network for the different land use scenarios.

Figure 5 provides a simple representation of the two future plans, the Mobility and Test Case 2030 scenarios. Apparently, the Test Case 2030 is a more concentrated plan alternative that higher density residential located closer to jobs along corridors and in activity centers contains a higher percentage of rural land and green space in the suburb. Thus, ideally, the transportation plan associated with the Test Case 2030 scenario ought to be aligned more closely with these assumptions.

The Mobility 2030 scenario represents the population and employment forecasts used in the development of Mobility 2030 transportation plan (ARC 2006). The scenario over-exaggerates job growth as a result of the manner in which the forecast model characterizes job density. Overall, the setting depicts a region that has substantial job growth in both core areas and suburbs. Characteristics of this

![Figure 5. Selected future transportation and land use scenarios (Courtesy of Atlanta Regional Commission).](image)
scenario include: distribution of growth based on available land, trends, and policy; proportional allocation of jobs with new households, small percentage of land available in 2030, even distribution of low density employment. The Test Case scenario is a centers-based and corridor-based approach with growth concentrated along the major roadways, interchanges, and exiting urban centers. This scenario uses local future land use plans, water and sewer plans, and other local policy as its foundation, but has been significantly influenced based on the input ARC received at the 17-county jurisdiction meetings with elected officials and staff. In many cases, when asked to identify the locations appropriate for development to accommodate the forecasted population and job growth anticipated in the county, local officials and staff situated growth along corridors and activity centers. Characteristics of this scenario include: higher density residential located closer to jobs along corridors and in activity centers, a higher percentage of housing accessible to transit, a higher percentage of rural land and green space, and a lower percentage of low density housing construction (ARC 2006).

3.5. Composite Sustainability Index (CSI)

Quantified performance measures can be weighted and aggregated to generate composite sustainability measures known as indexes (Organization for Economic Cooperation and Development (OECD) 1997). Indexes are generally easier to use, simple to interpret, and have the ability to reduce information overload resulting from individual performance measures (Lomax 1997). The construction of composite sustainability indexes proceeds in three steps: (1) generation of the raw indicator values, (2) normalization of the raw values, and (3) weighting of the normalized values. Through the weighted sum approach, composite sustainability indexes are aggregated by obtaining the weighted sum of normalized values for each performance measure. The use of weights is a controversial issue because it opens up the analysis to a certain amount of subjectivity. On the other hand, the use of weights also allows analysts and decision-makers to adjust weights over time as they learn which criteria are most critical. Weighting criteria can serve as an important tool to allocate the relative importance of the various criteria in an open policy arena, effectively incorporating regional goals and priorities. Typically, the weights are derived through an interactive process with decision-makers, allowing the weights to be adjusted over time (Zietsman et al. 2006). Sensitivity analysis should also be conducted on the weights to shed light on the relative overall impacts on the region of assigning various weights to the different sustainability factors. Thus, the composite index tool using the MCDM approach can be a relatively versatile tool for assessing tradeoffs among the different sustainability factors in decision-making to enhance sustainability.

This section demonstrates how a composite sustainability index can help evaluate the relative level of sustainability for different transportation plans or scenarios. Raw values of performance measures are quantified as described above, normalized to transform the various attribute values into comparable values, and weighted to represent relative significance of the different attributes. Table 2 shows the evaluation results of selected performance measures for three transportation and land use scenarios: Baseline 2005, Mobility 2030, and Test Case 2030 scenarios. As the value of the attributes increases, preferences of benefit attributes, A11 and
D12 (portions of spatial index), increase in a linear and monotonic manner while those of cost attributes, A21, B21, B23, C12, D12 (portions of income index), and D21, decrease in same manner.

Table 3 shows assigned weights for sustainability dimensions and performance measures as well as normalized indicator values for these three scenarios. These weights are derived from the attribute ranking method which essentially

Table 3. Criteria weights and normalized values.

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>Unit</th>
<th>Baseline 2005</th>
<th>Mobility 2030</th>
<th>Test case 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>A11. Average freeway speed</td>
<td>mile/hour</td>
<td>47.12</td>
<td>42.21</td>
<td>42.21</td>
</tr>
<tr>
<td>A21. Vehicle miles traveled per capita</td>
<td></td>
<td>35.04</td>
<td>31.75</td>
<td>31.75</td>
</tr>
<tr>
<td>B21. VOC emissions</td>
<td>ton/day</td>
<td>118.33</td>
<td>53.38</td>
<td>53.38</td>
</tr>
<tr>
<td>B23. NO_x emissions</td>
<td>ton/day</td>
<td>209.64</td>
<td>38.33</td>
<td>38.33</td>
</tr>
<tr>
<td>C12. Vehicle hours traveled per capita</td>
<td>minute/person</td>
<td>9.26</td>
<td>8.95</td>
<td>8.95</td>
</tr>
<tr>
<td>D12-1. Equity of VOC exposure (S)</td>
<td>Spatial Equity Index</td>
<td>19.10</td>
<td>23.45</td>
<td>23.45</td>
</tr>
<tr>
<td>D12-2. Equity of NO_x exposure (S)</td>
<td>Spatial Equity Index</td>
<td>20.02</td>
<td>23.56</td>
<td>23.60</td>
</tr>
<tr>
<td>D12-3. Equity of VOC exposure (I)</td>
<td>Income Equity Index</td>
<td>10.74</td>
<td>55.95</td>
<td>427.17</td>
</tr>
<tr>
<td>D12-4. Equity of NO_x exposure (I)</td>
<td>Income Equity Index</td>
<td>9.57</td>
<td>54.97</td>
<td>364.93</td>
</tr>
<tr>
<td>D21-1. Exposure to VOC emissions</td>
<td>Human Impact Index</td>
<td>1354.56</td>
<td>467.48</td>
<td>4134.47</td>
</tr>
<tr>
<td>D21-2. Exposure to NO_x emissions</td>
<td>Human Impact Index</td>
<td>2269.79</td>
<td>318.92</td>
<td>2766.65</td>
</tr>
</tbody>
</table>

VMT: Vehicle miles traveled.
VOC: Volatile organic compounds.
VHT: Vehicle hours traveled.

D12 (portions of spatial index), increase in a linear and monotonic manner while those of cost attributes, A21, B21, B23, C12, D12 (portions of income index), and D21, decrease in same manner.

Table 3 shows assigned weights for sustainability dimensions and performance measures as well as normalized indicator values for these three scenarios. These weights are derived from the attribute ranking method which essentially

Table 3. Criteria weights and normalized values.

<table>
<thead>
<tr>
<th>Criteria weights</th>
<th>Performance measures</th>
<th>Weights</th>
<th>Baseline 2005</th>
<th>Mobility 2030</th>
<th>Test case 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Transport (35%)</td>
<td>A11. Average freeway speed</td>
<td>0.67</td>
<td>1.000</td>
<td>0.896</td>
<td>0.896</td>
</tr>
<tr>
<td></td>
<td>A21. VMT per capita</td>
<td>0.33</td>
<td>0.906</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>B. Environmental (20%)</td>
<td>B21. VOC emissions</td>
<td>0.50</td>
<td>0.451</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>B23. NO_x emissions</td>
<td>0.50</td>
<td>0.183</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>C. Economic (10%)</td>
<td>C12. VHT per capita</td>
<td>1.00</td>
<td>0.967</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>D. Social (35%)</td>
<td>D12-1. Equity of VOC exposure (S)</td>
<td>0.12</td>
<td>0.815</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>D12-2. Equity of NO_x exposure (S)</td>
<td>0.12</td>
<td>0.848</td>
<td>0.998</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>D12-3. Equity of VOC exposure (I)</td>
<td>0.12</td>
<td>1.000</td>
<td>0.192</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>D12-4. Equity of NO_x exposure (I)</td>
<td>0.12</td>
<td>1.000</td>
<td>0.174</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>D21-1. Exposure to VOC emissions</td>
<td>0.26</td>
<td>0.345</td>
<td>1.000</td>
<td>0.113</td>
</tr>
<tr>
<td></td>
<td>D21-2. Exposure to NO_x emissions</td>
<td>0.26</td>
<td>0.141</td>
<td>1.000</td>
<td>0.115</td>
</tr>
</tbody>
</table>

VMT: Vehicle miles traveled.
VOC: Volatile organic compounds.
VHT: Vehicle hours traveled.
employs pair-wise preference judgments among attributes. The pair-wise judgment techniques help decision-makers logically compare two attributes at a time for the preference and determine the relative importance (ranking) of each attribute. By assigning 1 to the most important attribute and n to the least important attribute, the rank reciprocal weights can be obtained from the following formula (Yoon and Hwang 1995):

\[ w_j = \frac{1/r_j}{\sum_{k=1}^{n} 1/r_k} \]  

where \( r_j \) is the rank of the jth attribute. Normalized values for each alternative are determined by using a single-attribute utility function on linear normalized scales. The normalized ratings have a dimensionless unit, ranging from zero to one, in which the larger the rating becomes, the more preference it has (Yoon and Hwang 1995). Finally, Table 4 calculates the utilities for the three scenarios by obtaining the weighted linear sum for each of the sustainability criteria. The formulation of the composite sustainability index using the weighted sum model (WSM) is shown below (Yoon and Hwang 1995)

\[ U_j = \sum_{k=1}^{n} w_k n_{kj} \]  

where \( U_j \) is the utility of alternative j, \( w_k \) is the weight of the kth criterion, and \( n_{kj} \) is the normalized attribute k value for alternative j.

### 4. DISCUSSION: SUSTAINABILITY INDEX AS A DECISION-MAKING TOOL

Based on these four indexes for sustainable transportation, a profile graph can be drawn to effectively capture different levels of sustainability for the scenarios evaluated, as shown in Figure 6. While a full diamond shape is considered to be the maximum achievable level of sustainability for scenarios evaluated (based on the current sustainability goals/objectives and articulated scenarios), the area of each diamond conveys the relative level of comprehensive sustainability. The composite sustainability indexes for three alternatives are 69.8% (Baseline 2005), 73.1% (Test Case 2030), and 90.6% (Mobility 2030) using the pre-assigned weights for the sustainability dimensions as well as performance measures. These indexes

<table>
<thead>
<tr>
<th>Sustainability indexes</th>
<th>Baseline 2005</th>
<th>Mobility 2030</th>
<th>Test case 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Sustainability</td>
<td>0.317</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Social Sustainability</td>
<td>0.566</td>
<td>0.804</td>
<td>0.306</td>
</tr>
<tr>
<td>Transportation Effectiveness</td>
<td>0.972</td>
<td>0.927</td>
<td>0.927</td>
</tr>
<tr>
<td>Economic Sustainability</td>
<td>0.967</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Comprehensive Sustainability</td>
<td>0.698</td>
<td>0.906</td>
<td>0.731</td>
</tr>
</tbody>
</table>
indicate the Mobility 2030 scenario seems to be the best of the three alternatives when all factors are considered, and the Baseline 2005 scenario appears to be the least desirable. In the case of these three alternatives, the index shows that while the three scenarios seem to be comparable from a transportation system effectiveness and economic sustainability perspective, the main disparities are to be found in their environmental and social sustainability impacts. These differences may result from several assumptions that have been incorporated into the analyses to simplify the evaluation process. A certain amount of refinement is thus necessary before this tool be adopted as a robust decision-making tool.

Decision-makers in other regions with different priorities, however, may examine various tradeoffs across four indexes in terms of each sustainability dimension (See Table 4), weighted to reflect their priorities. The Baseline 2005 scenario, for example, represents the most sustainable (or least unsustainable) status in terms of transportation system effectiveness even though it eventually results in the lowest composite sustainability index. While the two future scenarios, Mobility 2030 and Test Case 2030, are considered to be plans that can enhance the overall sustainability of the transportation system, the Test Case 2030 scenario substantially decreases the level of social sustainability. This discussion can be effectively expanded based on the difference between dominance and tradeoffs between non-identical alternatives. While Mobility 2030 is dominant compared to the two other alternatives (i.e., the “Mobility” alternative is equal to or better than the “Baseline” and “Test Case” alternatives for all the four factors on the sustainability diamond), the index brings out the tradeoffs that are being made when comparing the “Baseline” and “Test Case” alternatives. While “Test Case” is a superior alternative from an environmental standpoint, the “Baseline” alternative is a superior alternative for advancing social equity. Thus, in moving from the 2005 Baseline scenario to the “Test Case” scenario, the overall gains made in
system-wide sustainability come from increases in environmental sustainability at the expense of social equity.

Understanding these types of tradeoffs can be valuable for understanding the impacts of decision-making on the region’s ability to achieve its current priorities. In cases where the overall sustainability score is negligible between two or more different scenarios, but there are definite differences in the scores of the four different sustainability factors, understanding the impacts of selecting one plan over another would entail understanding the tradeoffs that are being made from plan to plan. Therefore, the composite sustainability index as well as four basic sustainability indexes can function as decision criteria to identify the most sustainable (or least unsustainable) plan for predetermined weights. These weights, determined from regional priorities, are critical for deciding the relative emphasis placed on each dimension of sustainability. The fact that the regional priorities have been woven into the determination of the factors for the index indicates that the alternatives that surface as superior are superior from the standpoint of what is considered important with respect to the regional priorities. In other words, sustainability evaluation results may be different depending on weights or priorities of the different sustainability factors as determined based on the regional sustainability vision and goals. These uncertainties, meanwhile, suggest that decision makers should not just rely on a resulting index but must also examine the relevance of (1) weights and (2) evaluating process.

Thus, the versatility of this method lies in the fact that the index can continue to reflect changing regional priorities over time as the factors are weighted to reflect these priorities. In this way, decision-makers can be sure that the plan alternatives that are being chosen continue to reflect sustainability priorities within the region. It is important to note however that this tool defines the ideal for sustainability based on the “best scenario” in the alternatives put forward, rather than any absolute standard. And so it is perfectly plausible that two regions with identical conditions and regional sustainability priorities could end up with different sustainability diamonds depending on the quality of the planning alternatives they developed and put forward. Better alternatives would generate higher values on each axis of the sustainability diamond.

This tool could also be used to explore the implications of adopting different regional priorities by assigning different weights to reflect different sets of clearly articulated regional policies. A sensitivity analysis exercise could help shed light for decision-makers on how changing the emphasis on different regional priorities could most effectively result in desired regional outcomes. The research team plans to conduct sensitivity analysis of the results for the metro Atlanta region while refining the methods/models currently used to evaluate each index element.

5. LIMITATIONS OF THE STUDY

There are some limitations to this study. First, the methodology presented identifies the best plan from the competing alternatives put forward, and not necessarily the best plan for regional sustainability. Further research is necessary to link these sustainability indexes with objective sustainability measures in order to track the impacts of the plans on some objective scale of sustainability and enable
comparison of different regions on the basis of their progress toward sustainability. Second, the land use and transportation scenarios used in the study are not equilibria states from feedback effects between land use and transportation decisions. The use of an integrated transportation and land use model would enable the analyst to reflect more fully the sustainability impacts of different transportation and land use plans. Third, the performance measures actually evaluated to capture the sustainability goals and objectives of the Metropolitan Atlanta Region are a limited set from the full indicator list. Further development and quantification of sustainability measures will help incorporate the sustainability considerations more fully. Finally, some of the assumptions made in assigning weights to the different criteria could influence the resulting sustainability index values significantly. More work is necessary to refine the MCDM method, such as exploring fuzzy or Bayesian decision-making techniques, in order to effectively consider uncertainties associated with regional sustainability priorities.

6. SUMMARY AND CONCLUSIONS

As interest in sustainability has grown over the past several years, a growing number of Departments of Transportation (DOTs) has continued to include sustainability in their mission statements. However, few regional agencies have developed planning tools that successfully incorporate the comprehensive concept of sustainability (transportation system effectiveness, economic, environmental, and social sustainability) in the development of long-range plans, transportation improvement programs, and the selection of projects. This paper demonstrates an application of the multiple criteria decision making (MCDM) approach for incorporating the concept of sustainability in transportation decision-making to evaluate the relative level of sustainability for different transportation (and land use) plans or scenarios. The intent is to demonstrate how three different plans affect overall system sustainability differently based on regional priorities (i.e., regional plan goals, objectives, and performance measures). The study results show that the MCDM method, in conjunction with a composite sustainability index, can be used to identify clearly superior alternatives but also consider trade-offs that multiple scenarios present relative to the priorities placed on the different factors of sustainability. The MCDM/Sustainability Index tool is found to be particularly versatile relative to capturing regional priorities, which are not static, as a basis for evaluating competing plans. While the tool is applied at the plan level, the same concept can be used as a basis for developing a project-level tool to be used in propagating regional sustainability priorities in the selection of projects for implementation.

REFERENCES

C. M. Jeon et al.


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