Paper Submitted to

**2003 Annual Conference of the
Transportation Association of Canada**

A METHOD FOR QUANTITATIVELY PRIORITISING TRANSPORTATION PROJECTS ON THE BASIS OF SUSTAINABILITY

Bruce Hellinga
Associate Professor, Dept. of Civil Engineering
University of Waterloo
Waterloo, ON N2L 3G1
Email: bhellinga@uwaterloo.ca;
Phone: 519-888-4567 Ext. 2630

Ryan McNally
MASc Candidate, Dept. of Civil Engineering
University of Waterloo
Waterloo, ON N2L 3G1

A METHOD FOR QUANTITATIVELY PRIORITISING TRANSPORTATION PROJECTS ON THE BASIS OF SUSTAINABILITY

Bruce Hellinga and Ryan McNally
Department of Civil Engineering, University of Waterloo
Phone: 519-888-4567 Ext. 2630; Fax: 519-888-6197; Email: bhellinga@uwaterloo.ca

ABSTRACT

There is currently a great deal of interest in and discussion of the concept of sustainable transportation. A large number of factors, such as global warming, the Kyoto agreement, increased frequency and severity of poor air quality, that have provided the impetus for this increased interest. The scope of both discussions and research have, up to the present, focussed primarily on developing macroscopic measures of performance (or indicators) that are useful for application to regional areas. While these indicators are helpful for broad policy level evaluations, they are not always suitable for network and project level application. Consequently, transportation professionals and politicians at the municipal level have few, if any, tools available that enable them to quantitatively and objectively include sustainability when prioritising potential transportation projects. This paper addresses this issue.

Specifically, this paper presents several sustainability measures of performance and presents a framework within which these indicators can be used to evaluate potential transportation projects. The proposed method is illustrated using a sample transportation project.

1 Introduction

Sustainability is a ubiquitous term now attached to almost every policy developed by governments in the industrialised world. Yet, surprisingly there are few quantifiable methods for determining sustainability available. Despite this, there is a growing global consensus that there is a pressing need to achieve this as yet imprecisely defined goal of sustainability.

Transforming our current transportation systems to ones that are sustainable will require changes to the underlying relationships between the system components and to the priorities placed on different transportation modes. The change in the relationships will manifest themselves in changes to the physical structure of the transportation system, such as increased occurrence of bicycle lanes, and changes in the use of the system, such as increased use of cycling for transportation rather than recreation.

The challenge for transportation professionals, however, is to quantify the degree of sustainability of a proposed transportation project. It is within this context that we propose an evaluation framework and a set of candidate indicators that can be used to measure the changes in relationship (priorities), physical structure and use of the structures and whether or not these changes are leading towards or away from greater sustainability of the transportation system.

At this point it is necessary to define what is meant by *sustainable transportation*. There exists a large body of literature dedicated to sustainability and sustainable transportation. Despite this (or maybe because of this) there appears to be a lack of consensus on a concise definition of sustainable transportation. Nevertheless, the range of definitions provided in the literature capture several key issues including the use of non-renewable resources and social welfare.

For example, Meadows et al. (1992) indicate that sustainable transportation must address both useable materials, such as fossil fuels, and the capacity of global ecosystems to assimilate waste by-products of human activities.

When first promulgated by the United Nations World Commission on Environment and Development, sustainability was defined as “development that meets the needs of the present without compromising the ability of future generations to meeting their own needs;” needs were defined not as perceived needs of the affluent in industrial societies, but of “the essential [basic] needs of the world’s poor” (1980, p. 43, p. 80). The implication of this general definition of sustainability is that sustainable transportation must address not only resource stewardship issues (e.g. non-renewable resources) but must also consider social welfare issues such as equity of access for lower income groups.

This paper presents a decision making framework for use by transportation professionals in prioritising transportation projects on the basis of their respective impacts on a broad range of measures of sustainability. The method makes use of the concepts of multi-attribute decision making and attempts to provide transportation professionals and decision makers with a tool by which they can make informed decisions regarding the sustainability of proposed transportation projects.

This paper is organised as follows. The next section describes the development of a set of candidate indicators associated with five categories of sustainability. Section 3 describes the multi-attribute decision making process. Section 4 presents methods by which five candidate indicators can be quantified. In Section 5, the issue of weighting each candidate indicator is addressed. Application of the proposed decision making process to a fictitious set of transportation projects is provided in Section 6. Finally, conclusions and comments on future developed are provided in Section 7.

2 Measuring Sustainability

One of the most significant challenges in developing a decision support tool for assessing the sustainability of transportation projects is systematically defining appropriate indicators that capture key aspects of sustainability. In this research we have adopted a 5 step process (illustrated in Figure 1) for meeting this challenge.

In Step 1, we have reviewed existing literature and defined categories, or significant aspects, of sustainability. We also assembled a list of potential indicators that measure various aspects of sustainability (Step 2). In Step 3, each indicator is allocated to the category that the indicator measures most closely. In Step 4, each indicator is assessed for suitability against a set of three criteria. Step 5 consists of all those indicators that passed the criteria test from Step 4.

Each of these steps in this process is described in more detail in the following sections.

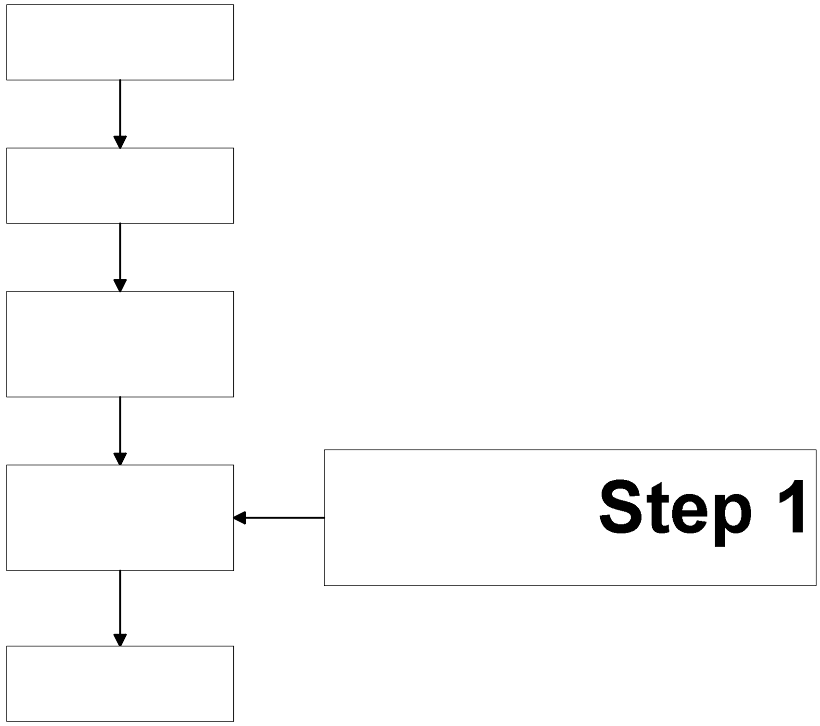

Figure 1: Process used to develop indicators of sustainability

2.1 Step 1: Establishing Categories of Sustainability

In this work we propose the use of five categories to characterise the various aspect of sustainable transportation. These categories, adapted from the work of Gibson (2001), are described below.

2.1.1 Integrity of Living Systems

Each of the living systems upon which humans depend must maintain its overall integrity, allowing for a state of dynamic equilibrium with response and adaptation to stresses on the system (Gibson, 2001). Indicators for this category measure the loss or gain of integrity related to changes in the transportation system.

2.1.2 Efficiency

The basic goal of efficiency is to reduce the material and energy demands made by transportation systems (Gibson, 2001). Efficiency indicators measure the volume of material and energy used and changes in those volumes. On its own, however, efficiency can be quite destructive, as increased efficiency that results in lower cost per unit travelled may lead to an increase in the overall consumption of transportation and consequently increased resource use (Hawken et al, 1999).

2.1.3 Sufficiency, Opportunity and Equity

A sustainable transportation system is one that provides access to services, employment, and experiences providing for a decent quality of material and social life and a realistic opportunity of improving the quality of life for all (Gibson, 2001). The indicators for this category measure the equity of access between those of different means and by different modes.

2.1.4 Decision-Making

Indicators in this category measure the ability to implement sustainable transportation within the framework of market-based economies, administrative and governmental policy development, societal customary practices and individual decision-making (Gibson, 2001).

2.1.5 Precautionary Short and Long-Term Action

There are two aspects to this category. The first is the limiting of action where the risks of the proposed actions are poorly understood (Gibson, 2001). It also includes the need to take action in the short term, but with a view to the long-term outcomes of the changes in the transportation system. Indicators in this category will measure the level of precaution related to risks and the ability for short-term actions to support long-term outcomes.

2.2 Step 2: Candidate Indicators

Indicators have been defined as "measurements that provide information on environmental states or aspects beyond those directly associated with the measurement itself" (Marbek, 1996, n.p.). Therefore, each measurement should provide information on the state of the category to which it belongs. For example, a measure in the Integrity of Living Systems category provides a measurement of the transportation systems effects on the integrity of livings systems within its sphere of influence. Furthermore, indicators should provide some direction as to the type of changes that render the transportation system more sustainable.

The candidate indicators proposed were developed through an iterative process, with the aim of arriving at a smaller set of workable, quantitative indicators. First, a large set of potential indicators was collected from the literature. Many of these indicators were summarised in the Centre for Sustainable Transportation Report No. 1, however, this list was supplemented by examining some other sources (see Dom, 2000; Environment Canada and Transport Canada, 1997, 2001Gilbert, 2000; Gilbert, 2001; Gilbert and Tanguay 2000; Gilbert et al 2002; Litman, 2000, Marbetk, 1996, Matley 2000; National Round Table on the Environment and the Economy, n.d.; Novak, 2002; OECD (Proceedings), 1997; O'Meara Sheehan, 2001; Oregon Solutions, n.d.; Sustainability Report, 2002; Tyrens and Silverman, 2000; Wackernagel and Reese; 1996). Subsequently, extra indicators were generated to fill in gaps in the list or to offer alternatives that appeared more easily used.

2.3 Step 3: Allocation of Indicators to Categories

The third step involved assigning the indicators to each of the five sustainability categories described in the previous section. It was observed that the efficiency category had by far the largest number of potential indicators, while the categories of Decision-Making and Precautionary Short and Long-Term Action had the fewest. It was noted that these two areas are inherently difficult to measure in a quantitative fashion, which explains the paucity of potential indicators.

2.4 Step 4: Assessment of Suitability of Indicators

Each indicator was then given a preliminary examination to see if it met three criteria. The first criterion was that the indicator would need to produce a quantitative measurement. Secondly, the indicator would need to be produced using data that is already being produced and collected, or that required minimal new data collection. Thirdly, to be of interest the indicator needed to be measure of sustainability that could be used at the project or local policy level.

During this process the list of potential indicators was reduced substantially. In the case of the Decision-Making there was no satisfactory quantitative indicator that appeared available at this time. In the case of Precautionary Short and Long-Term Action there was one quantitative indicator that remained; that indicator was land-loss. As land-loss was already an indicator in the Integrity of Living Systems category it was decided to eliminate this indicator from double counting. At this point it was decided to eliminate these categories from further consideration, thus the preliminary list of potential indicators was complete.

2.5 Step 5: Final list of indicators

Once the preliminary list of potential indicators was developed the indicators were examined using a variety of data. The purpose of this phase of examination was to determine the process for calculation each indicator. Through this process some of the indicators were modified from there original form. However, all modifications were undertaken to ensure that the indicators would be able to produce useable, quantitative data from readily available sources. It should be noted that the authors realise that these indicators are not definitive; there may be better measures or more precise methods of measuring that can be developed at a later date. Nonetheless, the indicators provided in Table 1 represent a starting point to make quantitative evaluations of the relative sustainability of transportation policies and systems.

Table 1: Candidate Indicators

Category	**Indicator**
Integrity of Living Systems	Land Loss Wetlands Agricultural Lands Forested Lands Total CO_2 equivalent emissions CO_2 equivalent emissions per trip unit (passenger)
Efficiency	Total Energy Consumption Energy Consumption per trip unit (passenger)
Sufficiency, Opportunity, Equity	Access to industrial and commercial space in a given mode specific commuter-shed Quality of Transportation Service (Transit) Jobs/Person in a given mode specific commuter-shed Comparative travel time by mode.

3 Decision-Making Process

Decision-making, using the indicators, was based on the use of Multi-Criteria Decision Making processes, and more specifically the use of Multi-Attribute Decision Making (MADM). Each of the categories of indicators and each of the indicators within a category was conceived of as an attribute to be used in the evaluation process. The use of MADM permits the combination of the attributes in an objective and quantifiable fashion.

The overall objective is to select projects that minimize a composite index of sustainability. This composite sustainability index captures attributes from all five categories of sustainability (Equation 1).

$$C_{Total} = \sum_{i=1}^{N} \left(C_i \beta_i \right) \tag{1}$$

C_{Total} = composite sustainability index
C_i = standardised indicator value for indicator *i*
β_i = weighting factor for indicator *i*
N = number of indicators

The composite measure is intended to give a quick overview of the relative sustainability of various transportation project choices. The overall value varies greatly depending on the total number of indicators used and other matters specific to the situation.

Application of Equation 1 requires that the standardised indicator value (C_i) and weighting factor (β_i) be known for each indicator *i*. The next section of this paper (section 5) describes the development of five candidate standardised indicators associated with three of the five categories of sustainability identified in Section 2.

The weighting of the indicators was achieved using a type of Analytic Hierarchy Process and is described in Section 6.

4 Calculating Standardised Values of Candidate Indicators

The following section defines five of the candidate indicators and provides the proposed calculation methodology. The indicators included are both emission related indicators, both energy consumption related indicators and a measure of the quality of transit service.

4.1 Integrity of Living Systems

4.1.1 Total Emissions

Human related greenhouse gas (GHG) emissions are considered the leading cause of climate change. Reducing emissions will slow climate change and hopefully help in maintaining planetary system integrity. Transportation is one of the major contributors of GHG and therefore one of the key sectors where reductions will be required. The following measure estimates the total GHG emissions associated with the transportation initiative being evaluated.

$$E_T = \sum K_i F_i \tag{2}$$

E_T = Total expected emissions observed in the horizon year, expressed as total mass.
K = Total expected vehicle kilometres travelled for the period, per vehicle type *i*.
F_i = Emission factor (CO_2 equivalent) for the vehicle type *i* (g/km).

Total vehicle kilometres for each mode within the area of interest are calculated and multiplied by the emissions factor for that mode (F_i). Total emissions are the sum of all the modal values and the relative emissions of various options can then be compared.

In order to convert this measure into a value that can be included in the composite sustainability index, the difference between projected total emissions (E_T) and a benchmark (B_{E_T}) is determined by dividing the projected value by the benchmark value (Equation 3).

$$C_{E_T} = \frac{E_T}{B_{E_T}} \tag{3}$$

C_{E_T}	=	The input for the composite measure, for the Total Emissions indicator.
E_T	=	the expected value from Equation 2.
B_{E_T}	=	The benchmark value for the specific indicator.

Meeting the benchmark would provide an "un-sustainability" score of 1.00, while values less than the benchmark would result in a fractional un-sustainability value. This is considered acceptable given that most benchmark values would represent reduction targets, but not an emission neutral or no impact scenario.

The benchmark value, B_{E_T}, would be calculated by reducing the present value of E_T by the reduction goal R_i, where R is the value of the goal for the indicator i. The normal policy process would determine the value of R_i. For example the process might determine that the value of R_{ET}, the reduction for total emissions, should be related to achieving the Kyoto Protocol targets. In order to achieve a value of six percent below 1990 levels, most sectors will need to reduce their emissions by approximately 30 percent below current (2003) levels (Thambimuthu, 2003). Therefore, the value of R_{ET} would be 30 percent. The value of B_{E_T} is computed using Equation 4.

$$B_{E_T} = G_{E_T} - (1 - R_{E_T}) \tag{4}$$

B_{E_T}	=	Benchmark value for use in equation (2)
G_{E_T}	=	Total mass of CO_2 being released in the base year, calculated using current data and Equation 2
R_{ET}	=	Reduction factor, expressed as a percentage.

4.1.2 Emissions Per Trip Unit

As mentioned previously, sustainability includes the need to reduce the intensity of use of resources associated with performing a particular task. For example, reducing emissions per kilometre travelled will reduce the use of emission processing and sequestration resources. Often intensity will be reduced through changes in technology.

An example of emission intensity reducing technology is the hybrid-electric vehicle, which increases fuel efficiency and consequently reduces emissions. However, as has been demonstrated in previous work such efficiency could be overcome by increased travel, and therefore taken alone it does not provide a full picture of advancement towards sustainability (McNally and Hellinga, 2002; 2002a). Yet, taken with the above measure of total emissions it can be an important indicator of the technological improvements or changes in the choice of technology that lead to reduced emission per unit of travel. Equation (5) outlines the measurement of this value for passenger transportation based on determining the mass of emissions per trip unit. A trip unit is either passenger kilometre (PKT) or a trip.

$$E_U = \frac{\sum K_{pi} F_i}{\sum U_i} \quad (5)$$

E_U = Emission per trip unit travelled
U_i = Total trip units (trips or PKT) per mode.
K_{pi} = Passenger related vehicle kilometres for mode *i*.
F_i = Emission factor for mode *i*.

The total trip units for passenger trips by all modes and the total emissions related to the passenger vehicles are calculated. The total passenger related emissions are then divided by total passenger trip units, in order to derive a value for E_u. The value of E_u can then be used to obtain the input for the composite measure.

Calculating the input value (C_{E_U}) for the composite indicator is undertaken in the same fashion as discussed in the previous indicator.

$$C_{E_U} = \frac{E_U}{B_{E_U}} \quad (6)$$

The benchmark value (B_{E_U}) would also be calculated using the same process (Equation 7). Again the choice of the R_i value would be determined through the policy process. For purposes of illustration, we have set the value of R_U at 30 percent.

$$B_{E_U} = G_{E_U} - (1 - R_{E_U}) \quad (7)$$

As per the previous indicator, achieving the benchmark would result in an un-sustainability score of 1.00, noting that the benchmark had been reached, but full sustainability had not.

4.2 Efficiency

4.2.1 Total Energy Use

As previously stated the sustainability of human systems will depend on the reduction of energy flows through the system, thus sustainable transportation must be significantly more energy efficient than is currently the case in Canada. Total energy use is an important measure of the energy efficiency of a transportation system. Equation 8 outlines the calculation of the total energy used by a specific transportation system or portion of a system.

$$En_T = \sum K_i Fn_i \quad (8)$$

En = Total energy used, expressed as MJ or GJ.
K_i = Total vehicle kilometres travelled by vehicle type *i*.
F_{ni} = Energy use factor, per vehicle kilometre, for the vehicle type *i* (J/km).

Total vehicle kilometres for each mode are calculated and multiplied by the energy use factor for that mode (Fn_i). Total energy use is the sum of the mode values. The energy use factors (Fn_i) are determined by using average fuel/electricity consumption for the type of vehicle and then multiplying estimated consumption by the energy conversion factor for the fuel type.

Benchmarking is used to calculate an input value for the composite indicator in the same fashion as is used to determine the emission related indicators; the benchmark is calculated as per Equations 3 and 4, making the necessary modifications to the subscripts.

A 75 percent reduction in energy use has been proposed as both possible and necessary to achieve overall sustainability by A. B. Lovins et al (1997); therefore, an R_{nt} value of 75 percent was used for the calculations of the benchmark value for this paper.

4.2.2 Energy Use Per Trip Unit

Reducing energy use per trip unit is also an important measure of increased energy efficiency, particularly when taken together with total energy use. Again, it is important that total energy use be examined as well to avoid making decisions that reduce per trip energy use while allowing total energy use to increase. Equation 9 defines the first part of this calculation.

$$U_{En} = \frac{\sum U_i}{\sum K_{pi} Fn_i} \qquad (9)$$

U_{En} = Passenger units travelled per energy unit used; usually expressed in Units/GJ.
K_{pi} = Passenger related vehicle kilometres for mode *i*.
U_i = Total trip units (trips or PKT) per mode.
F_{ni} = Energy use factor, per vehicle kilometre, for the vehicle type *i* (J/km).

The total energy related to the passenger vehicles and the total trip units for passenger trips by all modes are calculated. Total passenger trip units are then divided by the total amount of energy used to derive a value for U_{En}. Thus energy efficiency is expressed as trips taken per GJ of energy used. The value for total energy is the value determined for all passenger modes according to the methodology outlined in the Total Energy Use indicator.

Benchmarking is used to calculate an input value for the composite indicator in the same fashion as is used to determine the emission related indicators; the benchmark is calculated as per Equations 3 and 4, making the necessary modifications to the subscripts.

A 75 percent reduction in energy use has been proposed as both possible and necessary to achieve overall sustainability by A. B. Lovins et al (1997); therefore, a R_{Un} value of 75 percent was used for the calculations of the benchmark value for this paper.

4.3 Sufficiency, Opportunity, and Equity

4.3.1 Quality of Service

Transit is usually promoted as providing greater equity of transportation access for lower income groups, and reducing the cost of transportation for these groups. The quality of transit service offered, both in terms of the frequency of service and hours per day the service is available, is a relative measure of the equity between the transit dependent groups and those with automobile access. Secondly, in order to achieve greater ridership by choice riders, transit service must have a relatively high quality of service compared to the automobile. As increased transit ridership is usually connected to sustainability, because of reduced energy use and related emissions, transit service quality is one of the sustainability indicators chosen for demonstration in this paper.

The following measure of transit service quality is based on the Highway Capacity Manuel Level of Service guidelines for both frequency and hours of service. Similar measures could be developed for other modes and included in the composite indicator

The first step is to divide the area in question into transit route segments or potential route segments, differentiated by the quality of service offered. If the service level is that same for the entire route, then only one segment exists. For each segment the average number of vehicles per hour, for specific times periods, is determined. The time periods in question are morning peak

(0600-0859), mid-day (0900-1459), evening peak (1500-1759), early evening (1800-2059), late evening (2100-2359) and owl or overnight service (0000-0559).

The highest level of frequency proposed by the Highway Capacity Manuel results when there are more than six vehicles per hours passing a stop; at this frequency riders do not need schedules and the quality of service is considered Level A (HCM 27-4, ex 27-1). At LOS A, transit offers a more equitable service, in terms of trip initiation potential, with that of the private automobile. Therefore six vehicles per hour was the chosen benchmark value for this paper.

To calculate the Quality of Service-Frequency indicator for urban transit, the average number of vehicles per hour on the segment during each of the specified time periods is divided by the benchmark value of six. An average score for each segment, for the entire day, can then be calculated. The value for each segment or potential segment for the area in question is then averaged, resulting in an input for the composite measure. All transit modes (rail, bus etc.) are averaged together over the six daily time periods described above.

$$C_{QU} = \frac{\sum_{i=1}^{6} 1 - \frac{V}{6}}{6} \tag{10}$$

C_{QU} = The input value for the composite indicator (urban transit service).
V = Number of vehicles per hour

For the frequency of inter-city or commuter services travelling between urban areas, the Quality of Service-Frequency indicator is calculated by dividing the number of vehicles per day by 15; as service is measured on a daily basis trips are not broken down by time period. Fifteen vehicles per day is seen as an optimal level for providing numerous trip options and return trip options, and is thus seen as the appropriate benchmark value (HCM 24-7, exhibit 27-3, 2000). The value produced is then used in the composite scoring.

$$C_{QI} = \sum_{1 to i} 1 - \frac{V_i}{15} \tag{11}$$

C_{QI} = The input value for the composite indicator (intercity/commuter service).
Vi = Number of vehicles per day, for transit mode *i*.

When commuter services operate at frequencies of 60 or more trips per day, we suggest that they be evaluated using the urban transit methodology described previously, as the type of service being operated bares a greater resemblance to urban transit service than to inter-city service.

The number of hours of service per day is also considered an important measure of service quality. For urban transit services, the chosen benchmark value is 24 hours per day service, while for inter-city or commuter services the chosen benchmark is 18 hour per day. Both benchmark values represent a Level A (HCM 27-6, exhibit 27-4).

Measuring the quality of the number hours of service requires the use of Equation 12. The formula evaluates the difference between the current service level and the benchmark and expresses it as a value out of 1.00. If service hours match the benchmark value the score is 0.00, if there is no service the score is 1.00. The value produced is then used in the composite scoring.

$$C_{QH} = \sum_{1toi} 1 - \frac{H_i}{24} \tag{12}$$

C_{QH} = The input value for the composite measure.
H_i = Number of hours of service per day, for transit mode *i*.

In order to calculate the input for the composite measure, the value for C_{QU}/C_{QI} (represented as C_{QF}) and C_Q are summed together (Equation 13).

$$C_{QS} = C_{QF} + C_{QH} \tag{13}$$

C_{QS} = the Quality of Service input for the composite measure.

5 Weighting Factors

The weighting factors (β_i) in Equation 1 are by necessity subjective in nature as they reflect opinions regarding the relative importance of the individual indicators that comprise the composite sustainability index. Several techniques are available by which these weights can be obtained. In this paper, we propose the use of an Analytic Hierarchy Process (AHP) which divides the problem of estimating weights into two separate phases.

In the first phase, the relative weighting of each of the five categories of indicators is determined. In the second phase, the relative importance (weight) of each indicator within each category is determined. The final weighting for each indicator is determined as the product of the weighting from the first and second phase.

In both phases the relative weight is established using a pair-wise comparison technique in which only two alternatives are compared at a time. To illustrate, consider three attributes for which relative weights are to be determined. A 3 ×3 matrix is constructed as illustrated in Figure 2.

The diagonals of the matrix (i.e. cells 1, 5, and 9) are set equal to unity. Since the matrix is symmetrical about the diagonal, all cells above the diagonal are initially ignored and weights are determined only for each cell below the diagonal. For example, on the basis of expert opinion, it may be determined that indicator B is twice as important as indicator A and indicator C is only half as important as indicator A. Therefore, values of 2 and 0.5 are entered in cells 2 and 3 respectively. Similarly, a weight of 5 is entered into cell 6 indicating that indicator C is 5 times as important as indicator B. Since the matrix is symmetrical, the values for cells 4, 7 and 8 are equal to the reciprocal of the values in cells 2, 3, and 6, respectively (Figure 2a).

The weight in each cell of the matrix is normalized by dividing the weight by the sum of all weights in the same column. For example, the normalised weight for cell 2 is computed as 2/3.5 = 0.571. The sum of the normalised weights in each column must equal 1.0 (Figure 2b).

Finally, the attribute weights are determined by normalising the row totals by the matrix totals. For example, the attribute weight for Attribute A is computed as 0.988/3.0 = 0.329. The attribute weights for Attributes B and C are 0.263 and 0.408, respectively.

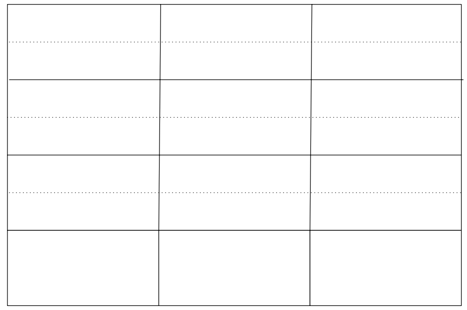

Figure 2(a)

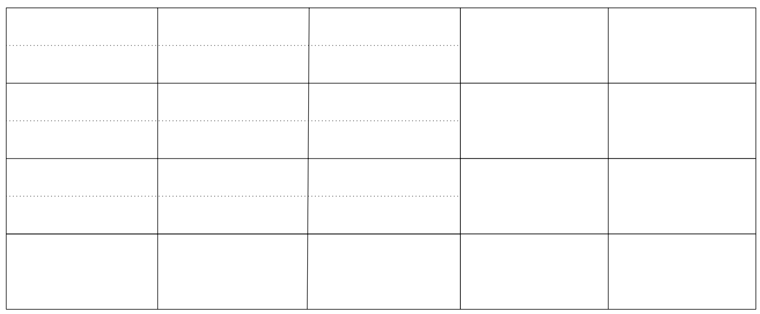

Figure 2(b)

Figure 2: Illustration of application of pair-wise comparison method for determining weights

Using this methodology a two-level AHP pair-wise comparison was developed to provide a weighting for the indicators used as examples in this paper. The first comparison was conducted between the five different categories of indicators, while the second comparison was of indicators within each category. Table 2 displays the results of the pair-wise comparison for the category weightings. Finally, the overall weighting for each indicator was determined by multiplying the category weighting by the weighting of the individual indicator (Table 3).

Table 2: Category Weighting Factors

Category	Integrity of Living Systems	Efficiency	Sufficiency, Opportunity and Equity	Citizen Participation	Precautionary Short and Long Term Action	Relative Weighting
Integrity of Living Systems	1 (0.58)	7 (0.26)	5 (0.77)	5 (0.44)	6 (0.37)	0.48
Efficiency	1/7 (0.08)	1 (0.04)	1/6 (0.03)	1/8 (0.01)	1/5 (0.01)	0.03
Sufficiency, Opportunity and Equity	1/5 (0.12)	6 (0.22)	1 (0.15)	5 (0.44)	6 (0.37)	0.26
Citizen Participation	1/5 (0.12)	8 (0.30)	1/5 (0.03)	1 (0.09)	3 (0.19)	0.14
Precautionary Short and Long Term Action	1/6 (0.10)	5 (0.19)	1/6 (0.03)	1/3 (0.03)	1 (0.06)	0.08
Total	1.71 (1.00)	27.00 (1.01)	6.53 (1.01)	11.46 (1.01)	16.20 (1.00)	0.99

(Rounding error is possible.)

Table 3: Indicator Weighting Factors

Indicator	Category Weighting	In-Category Weighting	AHP Weighting
Total Emissions	0.48	0.46	0.22
Emission per Trip Unit	0.48	0.31	0.15
Total Energy Consumption	0.03	1	0.03
Energy Consumption per Trip Unit	0.03	1	0.03
Quality of Service – Transit	0.26	0.13	0.03

6 Sample Application

As mentioned earlier the measures were individually tested with sample data either available from environmental study reports, public transit schedules, or generated specifically for the purposes of indicator development. However, there was no comprehensive, easily available data set that would permit testing of all the measures at once. Therefore, a simple test scenario was created. The scenario was designed to present “extreme” options for the corridor in question, and therefore it may not appear realistic compared to the types of situations currently considered by transportation professionals.

The test scenario was for a city of 300,000 persons with a neighbouring town of 80,000 persons. Over the course of the planning period total population was expected to grow to about 500,000. Together the communities form a planning region with the city providing the major source of employment for residents of the town. The city had three main employment areas consisting of the Central Business District (CBD), and East Side Major Employment Area and a West Side Major Employment Area.

Currently, commuters between the two municipalities have access to a two-lane roadway for movement between the two communities. An intercity coach company provides 20 daily round trips between the two communities with connections outside of the planning area. There are two daily round trips provided by a rail operator, again with connections to destinations beyond the planning area. Three different future transportation scenarios were under consideration for the connecting corridor.

The first scenario is the construction of major multi-lane limited access roadway between the two communities with connecting roadways at either end. Rail transit would continue to offer two daily round-trips, while coach trips would be increased to 25 roundtrips daily. Total traffic is expected to increase from 15,000 to approximately 44,000 AADT at the midpoint between the two communities. Daily coach ridership was expected to rise from 800 to 1,250, while rail ridership would remain at 432 persons per day.

The second scenario is the creation of coach HOV facilities to speed travel on the current roadway, and the expansion of coach service to 400 return trips per day, in order to accommodate all of the increase in passenger travel demand associated with the corridor. Coach service would change from a downtown-to-downtown pattern to a pattern of serving each of the major employment areas with express coach service. Access to local transit service would be eased, as the express coaches would provide more opportunities for interconnection. Rail service would remain at two round trips per day. Land use patterns would be of a higher density than in the first scenario, but would not necessarily be considered compact. Daily coach ridership was expected to rise from 800 to 31,200, while rail ridership would remain at 432 persons per day. AADT was expected to remain at approximately 15,000.

The third scenario would see all road infrastructure remain in its current state. Coach service would be increased marginally to 25 return trips per day. Rail infrastructure would be expanded, with new rail stations being constructed in both the East and West Employment Areas. Train service would increase to 90 return trips per day. Land use patterns would be much more compact under this scenario, with employment being concentrated near the new and existing train stations. Daily coach ridership was expected to rise from 800 to 1,250, while rail ridership would rise to 31,100 persons per day. AADT was expected to remain at approximately 15,000.

For each of the scenarios, the necessary background information and data was developed. Each of the indicators was then calculated using the methodology described in the previous section, with the values summed to calculate the composite score. The values are listed in the Table 4 below.

Table 4: Result of the Test Scenario

Category and Indicator	Raw Input for Composite Score: Major Highway Based Plan	Raw Input for Composite Score: Coach Based HOV Plan	Raw Input for Composite Score: Rail Based Plan	Weighting Factor	Weighted Input for Composite Score: Major Highway Based Plan	Weighted Input for Composite Score: Coach Based HOV Plan	Weighted Input for Composite Score: Rail Based Plan
Integrity of Living Systems							
Total Emissions	4.27	2.61	2.50	0.22	0.94	0.57	0.55
Emissions/Travel Unit	1.55	0.97	0.92	0.15	0.23	0.15	0.14
Efficiency							
Total Energy Consumption	4.04	1.78	1.61	0.03	0.12	0.05	0.05
Energy Consumption/Travel Unit	1.47	0.66	0.59	0.03	0.04	0.02	0.02
Sufficiency, Opportunity, Equity							
Quality of Service, Transit	1.37	(0.37)	(0.04)	0.03	0.04	(0.01)	(0.00)
	12.70	5.65	5.58		1.38	0.78	0.75

7 Conclusions and Future Directions

A framework has been developed for the implementation of a system of measurement that brings quantitative sustainability considerations into the transportation planning process. The framework is based on the assumption that at the broader landscape level, there is a desire to attain sustainability. In order to achieve sustainability, the patterns, structures and use of structure in the transportation landscape must change. The indicator system proposed is designed to measure that change.

The chosen indicators resulted from the examination of a large number of quantitative sustainability indicators of transportation system, and were grouped under the categories of Integrity of Living Systems, Efficiency, and Sufficiency, Opportunity and Equity. For each indicator examined, a method of deriving input for the calculation of a comprehensive indicator was devised. The relative weighting of each indicator was determined using the AHS pair-wise method. The specific and comprehensive indicators were then used to evaluate a set of transportation options for a fictional city-region corridor.

The indicators were successful in giving a comparative view of the sustainability of the three options. The roadway option was significantly less sustainable than either the coach or rail options, because of the higher total and per travel unit values of the GHG emissions and energy use indicators. This is as expected, as auto based transportation systems generally produce greater emission and use more energy than do mass transit based systems.

What is perhaps more interesting, is that the rail and coach based systems resulted in almost identical values. When examining the specific measures, it is apparent that the rail option was preferable in each case. However, the difference between rail and coach options was very small and therefore, it is difficult to firmly state that rail based option is the most preferable from a sustainability standpoint. Nonetheless, it is much clearer that either the coach or rail options are preferable over the highway option.

The comprehensive measure is far from complete. Under each category, there are likely other measures that upon further investigation would be important for inclusion in the measurement of sustainability. For example, under living systems integrity further measures could be defined for local air quality impact related to smog forming gases. Under equity, the distribution of costs and benefits to different socio-economic groups could also be included.

In the case of the two categories for which no measures are proposed, it is also important to find ways of quantifiably measuring these areas or at minimum, a more objective qualitative measurement that could be examined along with the quantitative measures for the other three categories.

In order to evaluate the potential for the use of the indicator set, it would be useful to use the measure to evaluate a series of transportation projects that have been planned and/or undertaken. Using the tools in a variety of situation would give a better sense of the importance of each measure and the significance of the absence of a measure.

Finally, further work can be undertaken to evaluate the effects of changes in R_i, benchmark and weighting values to determine how changes in these values would affect the overall outcome.

8 References

Capra, Fritjof (1996). The Web of Life: A New Scientific Understanding of Living Systems. New York: Anchor Book, Doubleday.

Décamps, Henri (2001). How a riparian landscape finds form and comes alive. Landscape and Urban Planning, 57, 169-175

Dom, Ann (2000). Are we Moving in the Right Direction? Indicators for Transport and Environment Integration in the European Union. In Transport Benchmarking: Methodologies, Applications & Data Needs. Paris: OECD Publications.

Egoaz, Shelly, Jacky Bowring and Harvey C. Perkings (2001). Tastes in tension: form, function, and meaning in New Zealand's farmed landscapes. Landscape and Urban Planning, 57, 177-196

Environment Canada, Canadian Wildlife Service and Ministry of Natural Resources (Ontario), Wildlife Branch (1984). An Evaluation System for Wetlands of Ontario: South of the Precambrian Shield, 2nd Edition.

Environment Canada and Transport Canada. (1997). Sustainable Transportation. Monograph No. 2, Prepared in connection with Canada' participation at the meeting of the United Nations Commission on Sustainable Development, April 1997. Ottawa :Ministry of Public Works and Government Services.

Environment Canada and Transport Canada. (2001). Sustainable Transportation: The Canadian Context. Monograph No. 15, A Canadian contribution to the dialogue at the Ninth Session of the United Nations Commission on Sustainable Development, April 16-27, 2001. Ottawa: Her Majesty the Queen in Right of Canada.

Gibson, Robert B. (2001) Specification of sustainability-based environmental assessment decision criteria and implications for determining "significance" in environmental assessment." Research and Development Monograph Series. Research supported by the Canadian Environmental Assessment Agency.

Gilbert, Richard (2002). Canada's Major Urban Regions: How they compare. Sustainable Transportation Monitor. Mississauga, Ontario The Centre for Sustainable Transportation, (7), 1-12.

Gilbert, Richard (2001, May). Potential Users and Uses of Sustainable Transportation Performance (STPI) Indicators: Final Report on Phase 2 of the STPI Project. Toronto: Centre for Sustainable Transportation.

Gilbert, Richard and Helene Tanguay (2000, June). Sustainable Transportation Performance Indicators Project: Brief Review of some Relevant World-wide Activity and Development of an Initial Long List of Indicators. Toronto: Centre for Sustainable Transportation.

Gilbert, Richard, Neal Irwin, Brian Hollingworth, Pamela Blais, Hon Lu and Nadia Brescacin (2002). Sustainable Transportation Performance Indicators Project: Report on Phase 3. Centre for Sustainable Transportation.

Hawkin, Paul, Amory Lovins, and L. Hunter Lovins (1999). Natural Capitalism. Boston: Little Brown and Company.

Litman, Todd (1999). Sustainable Transportation Indicators. Victoria, BC: Victoria Transport Policy Institute: www.vtpi.org.

Lovins, Amory B., L Hunter Lovins , von Weizacker, Ernst, (1997). Factor Four: Doubling Wealth, Halving Resource Use. London: Earthscan Publications Limited

Marbek Resource Consultants for Transport Canada (1996). Performance Indicators for Environmentally Sustainable Transportation – A Discussion Paper. Ottawa: Author.

Matley, Ted M., Lois M. Goldman and Brian J. Fineman (2000). Pedestrian Travel in Northern New Jersey: A Metropolitan Planning Organisation's Approach to Identifying Investment Priorities. IN Transportation Research Record 1705 (pp. 1-8). Washington, D.C.: Transportation Research Board – National Research Council.

M[c]Nally, Ryan and Hellinga, Bruce. (2002). Estimating The Impact Of Demographics And Automotive Technologies On Greenhouse Gas Emissions. 2002 Annual Conference of the Canadian Institute of Transportation Engineers.

M[c]Nally, Ryan and Hellinga, Bruce. (2002a). The Kyoto Ghg Emission Targets –

What Can We Expect From The Road Transportation Sector. 2002 Annual Conference of the Transportation Association of Canada.

Ministry of Natural Resources and Ministry of Municipal Affairs (1992). Manual of Implementation Guidelines for the Wetlands Policy Statement. Ontario; Queen's Printer for Ontario.

Meadows, Donella H., Dennis L. Meadows, Jorgen Randers (1992). Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future. Post Mills, Vermont: Chelsea Green Publishing Company.

National Round Table on the Environment and the Economy(n.d.). ESDI Initiative: Program Research, Summary of Cluster Group Recommendations. Accessed September 23, 2002, http://www.nrtee-trnee.ca/eng/programs/Current_Programs/SDIndicators/index.html.

Novak, Theresa. "Oregon: The state with the 'triple bottom line'." http://www.oregonfuture.oregonstate.edu/part3/pf3_03.html. Accessed September 23, 2002.

OECD (Proceedings) (1997). Towards Sustainable Transportation. Conference organised by the OECE, hosted by the Government of Canada, Vancouver, British Columbia; 24-27 March, 1996.

O'Meara Sheehan, Molly (2001). Making Better Transportation Choices. In Linda Sarke (Ed), State of the World 2001 (103-122) . New York: World Watch Institute, W.W. Norton & Company.

Oregon Solutions (n.d.). Sustainability in Oregon: Governor's Objectives for Sustainable Communities. Accessed September 9, 2002,

Sustainability Report (2002). Canada's Sustainability Indicators Initiative: The ESDI Approach to Indicators. Accessed September 23, 2002, http://www.sustreport.org/indicators/esdi_approach.html.

Thambimuthu, Kelly "Fossil Fuels, climate Change and Kyoto: Are we in a fix?" Public Lecture, TD Canada Trust – Walter Bean Professorship, University of Waterloo; March 18, 2003.

(2000). *Highway Capacity Manual*. Washington DC: Transportation Research Board.

Tyrens, Jeff and Bob Silverman (2000). Measuring Sustainability: The Role of the Oregon Benchmarks. Accessed September 9, 2002, http://www.econ.state.or.us/opb/sitemap.htm.

Satay, T.L. (1980) The Analytical Hierarchy Process. New York: McGraw-Hill,

Wackernagel, Mathis and William Rees (1996). Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriola Island, B.C.: New Society Publishers.

World Commission on Environment and Development (1987). Our Common Future. Oxford: Oxford University Press.