Modeling Sustainable Transportation Systems

by

Yuri Yevdokimov and Han Mao
Department of Economics, University of New Brunswick
Tel. (506) 447-3221, Fax: (506) 453-4514, E-mail: yuri@unb.ca

Abstract

Over time as population has increased, cities have grown, and globalization and free trade have increased the regional and international movement of people and goods, our transportation infrastructure and systems have expanded dramatically. However, our admirable achievements in terms of mobility have come at some considerable environmental as well as social and economic costs. The concept of sustainable development was specifically designed to evaluate the economic, environmental and social impacts of human activity.

A sustainable system implies interaction of three components: the economy, environment and society. Applied to transportation, this points at the necessity to establish interactive links of transportation with the economy, environment and society over time. Unfortunately, the structure and philosophy of the traditional approach to sustainability of transportation resulted in all expected developments in the transportation system being treated as consequences of isolated and once-and-for-all impacts. Usually these impacts are artificially imposed to evaluate different scenarios of the development of transportation over time. Sometimes, long-term goals are specified and various scenarios to reach these goals are evaluated. In any case, this is a one-directional process that does not take into account feedbacks between transportation and the economy, environment and society.

The novelty of the proposed approach is the addition of a normative aspect to the assessment of transportation's sustainability. It is designed to develop a methodology that not only evaluates current performance of a transportation system in terms of its positive and negative impacts on economy, environment and society, but also allows to derive a set of policy recommendations for the design of the sustainable transportation system. In this study, this goal is being achieved on the basis of economic theory and mathematical modeling.

In our approach, the modeling of the sustainable transportation system is based on the following principles: (i) aggregate sustainability criteria; (ii) treatment of sustainable transportation as a part of a three-dimensional system economy-environment-society, and (iii) system dynamics approach. These principles are explained in detail on the basis of economic theory and principles of mathematical modeling. As a result, theoretical structure for modeling sustainable transportation system is presented.

Introduction

Transportation contributes to the well-being of a nation by providing services of moving people and goods. In economics, the well-being of a nation is measured in terms of gross domestic product (GDP). Apart from its strategic role, the size of the transportation service industry in Canada in terms of GDP is significant. This sector is larger than the agriculture, fishing and trapping, logging and forestry industries combined. Since the growth of real GDP over time reflects economic growth, transportation in Canada should be regarded as a substantial contributor to the economic growth as well.

Numerically the importance of transportation can be measured using the system of national accounts in two ways: (i) through value-added (supply side); (ii) through expenditure (demand side). Value-added can be seen primarily as payments made by industry to workers or shareholders. It is a commonly used economic measure for assessing the relative importance of industries to the economy from production side. In the context of transportation, the value-added measure reflects the value added by transportation-for-hire or what is called commercial transportation.

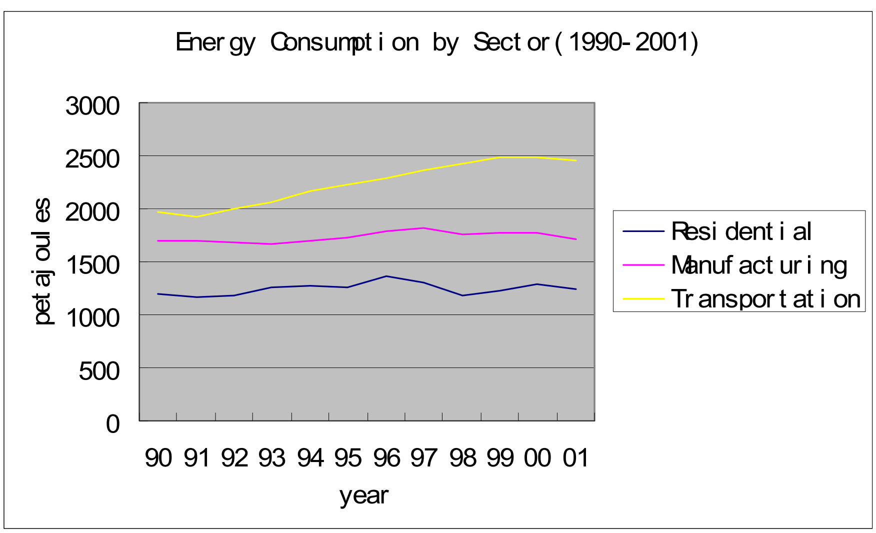
In turn, transportation demand refers to all expenditures on goods and services related to the transportation needs of households, private business and government. In contrast to the value-added by commercial transportation, it comes from final demand for all goods and services in the economy. Final demand is the sum of personal expenditures, investment, government spending and net exports. It describes the consumption side.

According to the annual report of Transport Canada in 2002, commercial transportation industries in Canada accounted for $39 billion or 4 percent of the value-added GDP. In turn, transportation expenditures amounted to $161 billion or 14.1 percent of total expenditures in Canadian economy. Besides, investment in transportation made up 3.3 percent of the GDP, which shows a 0.2 percent increase compared to 2001. Over the last five years until 2002, the number of full-time jobs related to transportation totaled more than 800,000.

However, over time as population has increased, cities have grown, and globalization and free trade have increased the regional and international movement of people and goods, our transportation infrastructure and systems have expanded dramatically. The cars, trucks, buses, subways, trains, airplanes, ships and ferries that we use to move ourselves and our goods today have significant implications in terms of energy and material resource use, environmental pollution, noise and land use at local, regional and global level.

1. Environmental and social impacts of transportation

In terms of energy use, in Canada transportation has been a chief consumer of energy for years as shown below:

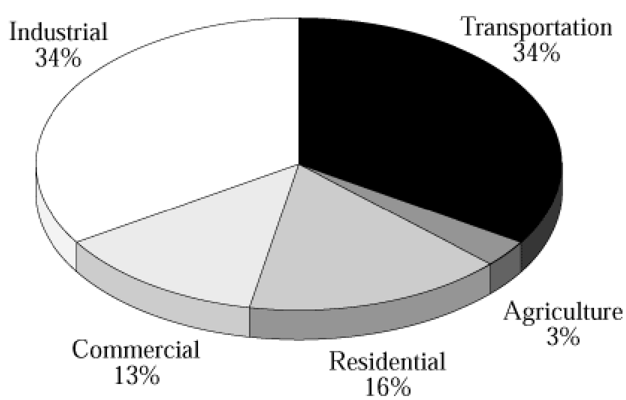


Source: Transport Canada Annual Report 2002

High energy consumption by transportation eventually resulted in significant negative environmental impacts. First of all, transportation is one of the major contributors to the climate change. Climate change is caused by active compounds, commonly called greenhouse gases or GHGs, that trap heat reflected from the surface of the planet in the lower atmosphere causing the greenhouse effect. The primary GHG is carbon dioxide, which is responsible for about two thirds of human-induced climate change.

The following figure 2 shows that in 2000, GHG emissions from Canada's transportation sector accounted for 34 percent or 163.4 megatonnes of total emissions from secondary energy use. This sector is the single largest source of GHGs in Canada. Of total transportation-related GHG emissions in 2000, road transportation accounted for almost 77 percent, the aviation sector 10.3 percent, and rail and marine combined for less than 9.5 percent.

Fig 2. GHG Emissions from secondary energy use in Canada, 2000



Source: Transport Canada Annual Report 2002

The following table 3 shows the amount of transportation-related emissions in Canada other than GHG that contribute to local environmental problems, such as acid rain and fog.

Table 3. Transportation-related emissions (except GHG emissions)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
CO (kt)	5,562	5,329	5,173	5,170	5,116	5,067	5,036	4,973	4,882	4,947	4,998
SO_2 (kt)	62	62	60	58	51	52	52	53	53	48	49
NO_x (kt)	735	700	698	701	708	710	703	723	717	719	720
VOCs (kt)	609	591	578	585	582	580	584	586	579	587	590

Source: The Centre for Sustainable Transportation, Sustainable Transportation Performance Indicators-Underlying Data and Calculation, March 2003

In addition, development of transportation requires vast areas of land. The following table 4 shows the estimated portion of land devoted to roadways in Canada and other countries. These values are relatively small when measured as a portion of total land area, but roads and parking facilities tend to be concentrated in urban areas where their impacts and opportunity costs are relatively large.

Table 4. Land area devoted to roadways (Brown, 2001)

	Roadway Rights of Way	Portion of Total Land Area	Area Per Capita	Area Per Motor Vehicle
	Hectares		$Meters^2$	$Meters^2$
United States	15,920,615	1.7%	573	746
Canada	2,276,656	0.2%	734	1319
Mexico	863,832	0.4%	87	1100
Japan	1,316,591	3.5%	104	184
France	1,020,586	1.9%	173	308
Germany	749,725	2.1%	91	164
United Kingdom	425,149	1.8%	72	137
Sweden	241,146	0.6%	268	566

Source: Victoria Transport Policy Institute, Land Use Evaluation (http://www.vtpi.org/tdm/tdm104.htm#_Toc5552718)

Among negative social effects of transportation, injuries and fatalities arising from different accidents are of major concern. The following table 5 shows injuries and fatalities arising from road transport activity in Canada.

Table 5. Injuries and fatalities arising from road transport activity

	1990	1991	1992	1993	1994	1995	1996	1997	1998
Injuries	262,680	249,217	249,821	247,588	245,110	241,935	230,890	221,349	217,614
Fatalities	3,963	3,690	3,501	3,615	3,263	3,351	3,091	3,064	2,927

Source: The Centre for Sustainable Transportation, Sustainable Transportation Performance Indicators-Underlying Data and Calculation, March 2003

These negative environmental and social impacts of transportation led to the following conclusion made by the Organization for Economic Cooperation and Development (OECD, 2001): "*…Our current transportation system is not on a sustainable path. Our admirable achievements in terms of mobility have come at some considerable environmental as well as social and economic cost. The challenge now is to find ways of meeting our transportation needs that are environmentally sound, socially equitable and economically viable".*

But what is meant by sustainable transportation? According to the Transport Canada "*the goal of sustainable transportation is to ensure that environmental, social, and economic considerations are factored into decisions affecting transportation activity*" (Transport Canada, 1999). According to Richardson (1999), a sustainable transportation system is "*one in which fuel consumption, vehicle emissions, safety, congestion, and social and economic access are of such levels that they can be sustained into the indefinite future without causing great or irreparable harm to future generations of people throughout the world."* The Environmental Directorate of the OECD defines environmentally sustainable transportation as *"transportation that does not endanger public health or ecosystems and that meets needs for access consistent with (a) use of renewable resources that are below their rates of regeneration, and (b) use of non-renewable resources below the rates of development of renewable substitutes."*

However, the best definition of a sustainable transportation system (STS) was given by the Canadian Centre for Sustainable Transportation:

A sustainable transportation system is one that:

• *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;*

• *is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy;*

• *limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.*

In order to find out whether or not we are on a path of sustainable transportation, we first need some comprehensive sustainability criteria that reflect all three components of sustainable development - the economy, society and environment. Furthermore, since the goal of this study is to model the STS, justification and specification of sustainability criteria have become especially important in this process.

2. Existing approaches to measure sustainability of transportation

Over the years, economic, social and environmental impacts have traditionally been treated as separate issues. This is reflected in the criteria commonly used to assess these impacts. For example, some traditional indicators include atmospheric concentrations of certain gases for the environment, employment rates for society and GDP for the economy. The main problem with these indicators is that they measure each aspect as if it were independent from the other two. In reality the economy, society and environment are linked in many ways which must be reflected in sustainability criteria. Literature review allows us to claim that all sustainability measures with respect to transportation can be divided in two broad groups: (i) Sustainable Transportation Performance Indicators (STPI), and (ii) aggregate sustainability criteria (ASC).

1.1. Sustainable Transportation Performance Indicators (STPI)

It turns out that the number of sustainability indicators within a given set may be highly variable creating difficulties in collecting data and interpreting the results. A set of relevant indicators can be selected from a pre-defined list or it can be tailor-made. Currently in Canada, five different sets of indicators measuring sustainability of transportation are being issued by five different institutions. The diversity of all indicators is amazing. In order to better understand this approach, let us take a closer look at the STPI designed by the Canadian Centre for Sustainable Transportation.

In December of 2002, the Centre produced initial set of 14 sustainability indicators that can be used to track progress towards or away from sustainable transportation in Canada. The following table 6 shows all 14 indicators:

Table 6 .The Sustainable Transportation Performance Indicators (STPI)

Indicator	Description
Indicator 1: Energy use for transport	This indicator represents the consumption of non-renewable fossil fuel resources for transport.
Indicator 2: Greenhouse gas emissions	This indicator represents greenhouse gas (GHG) emissions from transport in Canada.
Indicator 3: Other transport emissions	This indicator is an index that represents emissions of four locally acting pollutants
Indicator 4: Injuries and fatalities	This indicator is an index that represents injuries and fatalities arising from road transport activity.
Indicator 5: Movement of people	This indicator represents the total motorized movement of people within Canada.
	This indicator represents the total motorized

Indicator 6: Movement of freight	movement of freight within Canada.
Indicator 7: Travel by cars and planes	Indicator 7 is a refinement of Indicator 5, which concerns overall movement of people in Canada.
Indicator 8: Movement of personal vehicles	This indicator represents the total distance traveled by personal vehicles in vehicle-kilometres.
Indicator 9: Urban land use	This indicator represents the use of urban land by urban residents.
Indicator 10: Length of paved roads	This indicator represents the length of paved roads in Canada.
Indicator 11: Household spending	This indicator represents household spending on transport in relation to total after-tax spending.
Indicator 12: Relative transit costs	This indicator is an index that represents the cost of urban transit fares relative to the main variable cost of operating an automobile, namely fuel cost.
Indicator 13: Energy intensity of cars and Trucks	This indicator is an index that represents the amount of fuel used per kilometre by cars and trucks of all sizes.
Indicator 14: Emissions intensity	This indicator is an index that represents the rates at which road vehicles produce locally acting pollution.

Source: Canadian Centre for Sustainable Transportation

2.2. Aggregate Sustainability Criteria (ASC)

In terms of aggregate sustainability criterion, two such criteria exist: the Index of Sustainable Economic Welfare (ISEW), and the Genuine Progress Indicator (GPI). Both are economic measures because they are expressed in monetary terms, and both are associated with adjustments of the GDP to take into account social and ecological dimensions of the sustainable development.

The ISEW was developed by the Friends of Earth (United Kingdom) in association with the Centre for Environmental Strategy (CES) and the New Economics Foundation (NEF). It recognizes that *"GDP takes no account of increasing inequality, pollution or damage to people's health and the environment"* (Friends of the Earth, 2002). It is assumed in the GDP that any economic activity is good regardless of whether this activity improves or directly damages our quality of life. In this regard, the ISEW corrects GDP over a range of issues such as income inequality, environmental damage and depletion of environmental assets. It has been already calculated for nine countries, European Union and Chile.

In 1995, Redefining Progress - a nonprofit public policy and research organization in USA - created an alternative measure of economic progress called the Genuine Progress Indicator (GPI). The GPI takes into account more than twenty aspects of our economic lives that the GDP ignores. It includes estimates of the economic contribution of numerous social and environmental factors that the GDP dismisses. It also differentiates between economic transactions that add to well-being and those that diminish it. The GPI then integrates these factors into a composite measure so that the benefits of economic activity can be weighed against the costs. Technically, the GPI starts with the same personal consumption data the GDP is based on, but then makes some crucial distinctions. It adjusts for certain factors such as income distribution, adds certain others such as the value of household work and volunteer work, and subtracts others such as the costs of crime and pollution. The GPI for the United States and Australia has been calculated by the experts of Redefining Progress since 1950.

With respect to transportation, both ISEW and GPI include value of services provided by transportation infrastructure, cost of commuting, cost of automobile accidents, air and noise pollution by transportation, costs of lost farmlands and wetlands and others.

Both STPI and ASC have their own advantages and drawbacks. First, selection of a set of “good” indicators is a difficult task, both in terms of ensuring the number is manageable and that each indicator conforms to as many of the characteristics as possible. As well, some sets of indicators may send conflicting messages when different indicators point in different directions making it difficult to understand and interpret the overall result. Therefore, we don’t know, in general, whether the development of our transportation is on a sustainable path or not and at what speed. In addition, it is very difficult to use a set of indicators to model a sustainable transportation system.

In turn, aggregate criteria can help us to address some problems by presenting a general picture as a summary avoiding the details of various indicators, included in a set. Moreover, unlike set of various indicators, an aggregate criterion can be measured in the same way as some existing, generally accepted criteria to achieve its comparability with them. This would make it easier to interpret the results. The drawback, however, is that the general picture may provide misleading information when one dimension significantly over-weighs the other.

In a mathematical sense, an aggregate criterion represents an objective function that incorporates different characteristics of an object under study through a set of relevant variables. It can be easily formalized for modeling purposes. The dynamic nature of aggregate sustainability criteria – the ability to capture long-run trends along with the short-run fluctuations – makes them attractive for the use as sustainability criteria in the development of the STS model. Since the major task of this study is such modeling, the use of aggregate criteria seems to be more appropriate. In this research, the GPI was chosen for this purpose.

3. Modeling a sustainable transportation system

As literature review shows, so far the assessment of transportation's sustainability in Canada has been subject of a positive analysis. The question asked was whether or not our current transportation system is on a sustainable path. At large this approach conforms to the following three principles:

1. Sustainable Transportation Performance Indicators (STPI)
2. Isolated impacts of transportation on economy, environment and society
3. Benefit-cost analysis as analytical framework

Actually the second and third principles are direct consequences of the first one. Once STPI are chosen to measure sustainability of transportation, then all positive and negative impacts of transportation on economy, environment and society must be evaluated separately as either costs or benefits. What is wrong with this approach?

First, some disadvantages of the STPI were already discussed. It is also necessary to mention that each of the indicators in the set can be understood by an expert in relevant area only, not by general public. Furthermore, all these indicators are measured in their own units and are associated with a narrow aspect of transportation. In contrast, ASC in general and GPI in particular are expressed in monetary terms and based on a system of national accounts. In a sense, they are measures of social well-being consistent with economic theory and practice. In addition, they are easy to interpret and communicate.

Second, by definition, a sustainable system implies interaction of three components: the economy, environment and society. Applied to transportation, this points at the necessity to establish interactive links of transportation with the economy, environment and society over time. However, the structure and philosophy of the benefit-cost analysis, used in traditional approach to evaluate sustainability, result in all expected developments in the transportation system being treated as consequences of isolated and once-and-for-all impacts. Usually these impacts are artificially imposed to evaluate different scenarios of the development of transportation over time. Sometimes, long-term goals are specified and various scenarios to reach these goals are evaluated. In any case, this is a one-directional process that does not take into account feedbacks between transportation and the economy, environment and society.

Third, the benefit-cost analysis was designed to evaluate specific projects. In other words, it was designed to assess marginal changes within an existing system. Sustainability is a very long-run concept. It means that the time horizon, associated with the STS, involves more than one generation. Hence, evaluation of sustainability of transportation must be viewed in terms of structural (system) changes rather than marginal changes which points at methodological inapplicability of the benefit-cost analysis.

The novelty of this approach is the addition of a normative aspect to the assessment of transportation's sustainability. It is designed to develop a methodology that not only evaluates current performance of a transportation system in Canada in terms of its positive and negative impacts on economy, environment and society, but also allows to derive a set of policy recommendations for the design of the STS. In this study, this goal is being achieved on the basis of economic theory and mathematical modeling.

In our approach, the modeling of the STS is based on the following principles:

1. ASC instead of the STPI
2. Treatment of sustainable transportation as a part of a three-dimensional system economy-environment-society instead of separate evaluation of transportation impacts on economy, environment and society
3. System dynamics approach instead of benefit-cost analysis

Since advantages of the ASC for modeling STS were discussed previously, the other two principles should be explained in more detail.

Second principle is associated with what we call s*ystems approach to sustainable transportation.* In 1997, the US Transportation Research Board pointed out that *"…sustainability is not about threat analysis; sustainability is about systems analysis. Specifically, it is about how environmental, economic, and social systems interact to their mutual advantage or disadvantage at various space-based scales of operation"* (TRB, 1997). However, in all existing models of sustainable transportation system, transportation is presented as a separate module and then potential impacts of transportation on economy, environment and society are evaluated.

In addition, the existing framework, designed to evaluate sustainability of transportation, uses two interpretations of sustainability: (i) sustainability as combination of any two out of three dimensions of sustainable development economy-environment-society; (ii) comprehensive sustainability as combination of all three dimensions of sustainable development (Canadian Centre for Sustainable Transportation, www.cstctd.org). Therefore, according to this framework, anything that, for example, improves environmental performance of transportation would be called sustainable transportation which contradicts general notion of sustainability in economic theory.

In the proposed approach, a system that consists of three elements (i) economy, (ii) environment and (iii) society is established first. Then the approach places transportation network within the economic component of the system and develops its links with environment and society. Structurally transportation network is incorporated in such a system through vertical and horizontal linkages.

Horizontal linkages are links of a transportation network with environment and society outside the economic component. Examples of these links are:

Environmental links:

- emissions;
- noise pollution;
- land use;
- utilization of natural resources.

Social links:

- safety;
- mobility;
- accessibility.

Vertical linkages are links of a transportation network with other sectors of an economy within the economic component. These links capture interaction of transportation network with other sectors of the economy as well as some social values of transportation not included in GDP. Fig. 7 graphically represents the structure underlying the systems approach to sustainable transportation:

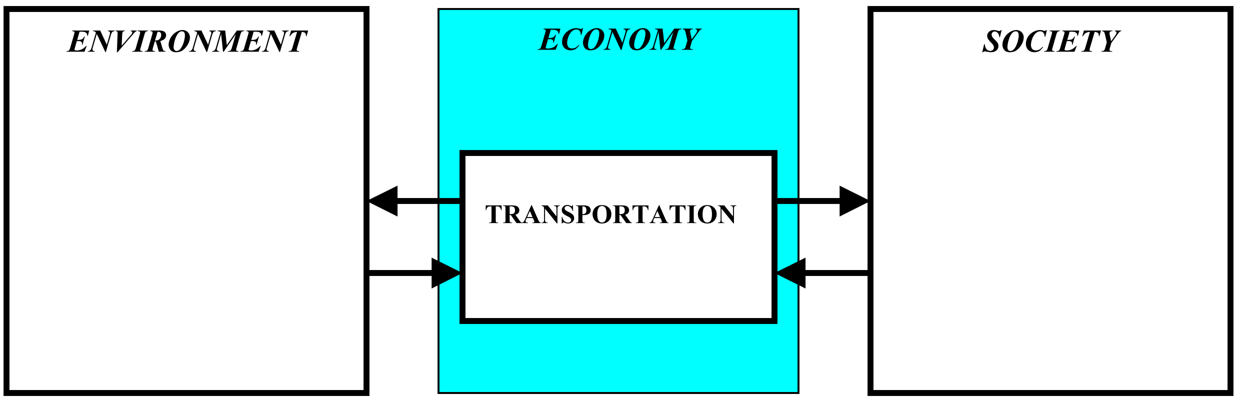


Fig 7. Systems approach to sustainable transportation

Advantages of such an approach are:

- consistent with real world;
- easily identifiable structure;
- explicit links and feedbacks.

Third principle is associated with the *system dynamics approach.* The approach is based on the statement that a system must evolve according to the state-flow relationships organized in feedback loops. Compared to the benefit-cost analysis, the system dynamics approach captures interaction between the system's components as well as the system's feedbacks. Instead of the forced, one-directional design of the benefit-cost analysis, in the system dynamics approach intrinsic dynamics of the system drive it through time which reflects the so-called self-organization of the system. As a result, the system under study evolves over time. The approach is perfectly applicable to the modeling of the STS as a part of economy-environment-society system since all the vertical and horizontal linkages of the transportation network can be captured through state-flow relationships over time.

Furthermore, according to the concept of sustainability developed by Vester (1980) within the system dynamics approach, a system that evolves exponentially is not sustainable. It implies that if we added sustainability constraints to the system's dynamics, we would end up with the required time path for the STS plus a set of necessary conditions to achieve this time path.

Therefore, we propose the following structure to model the STS:

(i) specification of the initial conditions;

(ii) description of the system dynamics,

(iii) aggregate sustainability constraint.

Initial conditions should consist of two sets: (i) economic fundamentals, and (ii) policy variables. Economic fundamentals will describe the economy's existing state of technology and current preferences of the society. In turn, policy variables will include the existing institutional foundations that go along with economic fundamentals.

System dynamics is based on a set of the state-flow relationships of the type:

$$V_{t+1} = V_t + \Delta V_t(F, P)$$

where V_{t+1} is the state of the transportation system next period, V_t is the sate of the transportation system now and ΔV_t is the change in the state of transportation system as a function of economic fundamentals F and policy variables P. This is a mathematical model that will capture vertical linkages of a transportation network as defined before.

Aggregate sustainability constraint is

$$\Delta GPI_{t+1} = VA_{t+1} \pm \sum_{i=1}^{N} E_{i(t+1)} \geq 0$$

where ΔGPI_{t+1} is the change in the GPI due to transportation, VA_{t+1} is the value added by commercial transportation, $E_{i(t+1)}$ is the *i-th* positive or negative economic, environmental and social effect not included in the GDP. Aggregate sustainability constraint will capture horizontal linkages of the transportation network.

If the aggregate sustainability constraint is satisfied, the system dynamics drive the system over time. If the aggregate constraint is not satisfied, changes to economic fundamentals F and/or policy variables P are imposed. In the end, the system dynamics will produce a sustainable path of the transportation system under study plus a set of the required changes to economic fundamentals and policy variables.

Conclusion

The existing in Canada approach to sustainability of transportation is based on positive analysis. The approach answers the question whether or not our current transportation system is on sustainable path. In answering this question, a set of sustainable transportation performance indicators was produced. Coupled with social benefit-cost analysis the set of indicators is being used to measure some isolated positive and negative economic, environmental and social impacts of transportation.

Since normative aspect of the transportation's sustainability was not properly addressed in the existing traditional approach, a mathematical modeling based on aggregate sustainability criteria, systemic analysis and system dynamics approach can be a better option. It can simultaneously address both positive and normative aspects of the transportation's sustainability.

References

Friends of Earth, http://www.foe.co.uk

OECD, http://www.oecd.org/home/

Richardson, B., "Towards A Policy On A Sustainable Transportation System", *Transportation Research Record* 1670, 1999, pp. 27-34.

Redefining Progress, http://www.rprogress.org

The Centre for Sustainable Transportation, *Sustainable Transportation Performance Indicators-Underlying Data and Calculation,* March 2003, http://www.cstctd.org/

The Centre for Sustainable Transportation, *Definition and Vision of Sustainable Transportation*, October 2002, http://www.cstctd.org/

Transport Canada, *Transportation in Canada Annual Report 1996-2002,* www.tc.gc.ca

Victoria Transport Policy Institute, http://www.vtpi.org

Yuri Yevdokimov, "Sustainable Transportation System: A System Dynamics Approach", *Proceedings of the 37th Annual Conference of Canadian Transportation Research Forum*, St. Johns, May 12-15, 2002, 488-500