Addressing Sustainability in Transportation Systems: Definitions, Indicators, and Metrics

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Abstract: Addressing the sustainability of transportation systems is an important activity as evidenced by a growing number of initiatives around the world to define and measure sustainability in transportation planning and infrastructure provision. This paper reviews major initiatives in North America, Europe, and Oceania. The purpose is to characterize the emergent thinking on what constitutes transportation sustainability and how to measure it. While there is no standard definition for transportation system sustainability, it is largely being defined through impacts of the system on the economy, environment, and general social well-being; and measured by system effectiveness and efficiency, and the impacts of the system on the natural environment. Frameworks based on important causal relationships between infrastructure and the broader environment, infrastructure impacts on the economy, environment, and social well-being; and the relative influence of agencies over causal factors, are largely being used to develop and determine indicator systems for measuring sustainability in transportation systems. Process-based approaches involve community representatives and other stakeholders in planning and present opportunities to educate the public and influence collective behaviors. These frameworks can be used collectively to help agencies refine their visions as well as develop policies, planning procedures, and measurement and monitoring systems for achieving sustainable transportation systems.

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Introduction

The most widely used definition of sustainable development, from the Brundtland Commission, is the basis of most definitions for sustainability in various national economies: Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). Since sustainable development became an international priority in the 1980s and 1990s, infrastructure sustainability has become a growing area of interest in practice, research and education [see, for example, OECD (1999b); Segnestam (1999); Gilbert and Tanguay (2000); Gudmundsson (2000); Meyer and Jacobs (2000); Rijsberman and van de Ven (2000); Deakin (2001–2003); Ashley and Hopkinson (2002); Balkema et al. (2002); Black et al. (2002); Pearce and Vanegas (2002); Bannister and Pucher (2003); CST (2003); Cortese (2003); Federico et al. (2003); Litman (2003); Wheeler (2003)]. In planning for transportation and other infrastructure systems, several agencies have adopted sustainability within their mission statements. Table 1 shows how the mission statements of various Departments of Transportation (DOTs) in the United States capture the concept of sustainability. The missions were culled from a search of the websites of the 51 State DOTs. They indicate that operational definitions of transportation system sustainability, while varied, capture attributes of system effectiveness and efficiency, and system impacts on the economy, environment, and social quality of life.

What is transportation system sustainability? How is it being measured? What types of policies are being used to promote or cultivate progress toward sustainable transportation systems? The answers to these questions will be useful to practitioners who are interested in implementing policies, planning procedures, and decision support systems to move toward transportation system sustainability as defined in their missions. They will also benefit researchers interested in advancing analytical tools and policy instruments, as well as educators interested in expanding their existing curricular to address sustainability in civil infrastructure systems.

This paper assesses selected sustainable transportation initiatives in North America, Europe, and Oceania to characterize the current state of thinking on what constitutes sustainability in transportation system planning and provision, and how it is measured. First, the authors review definitions; indicators and metrics of transportation (and other infrastructure) systems sustainability based mainly on 16 sustainability initiatives (in practice and research) in North America, Europe, and Oceania, as well as selected research initiatives in the literature. The terms indicators and metrics are used to refer to qualitative and quantitative measures of sustainability, respectively (Web Definitions (Indicators); Web Definitions (Metrics)). The literature review is based on the transportation and urban planning literature, infrastructure systems, and sustainability literature, as well as web-based reports documenting work either in progress or recently completed by various organizations and agencies. Next, the authors assess the

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Table 1. Sustainability in Missions of the State Departments of Transportation (United States)

Departments/Agencies of Transportation	Mission statement
United States Department of Transportation (Federal)	"Serve the United States by ensuing a fast, safe, efficient, accessible and convenient transportation system that meets our vital national interests and enhances the quality of life of the American people, today and into the future." ⟨http://www.dot.gov/mission.htm⟩
Florida	"The Department will provide a safe transportation system that ensures the mobility of people and goods, enhances economic prosperity and preserves the quality of our environment and communities." ⟨http://www.dot.state.fl.us/publicinformationoffice/moreDOT/mvv.htm⟩
Georgia	"We the members of the Transportation Board, the Commissioner and the employees of the Georgia Department of Transportation, are committed to a safe, efficient and sustainable transportation system for all users." http://www.dot.state.ga.us/specialsubjects/aboutgdot/index.shtml⟩
Indiana	"Our mission is to provide our customers with the best transportation system that enhances mobility, stimulates economic growth, and integrates safety, efficiency and environmental sensitivity." ⟨http://www.ai.org/dot/⟩
Louisiana	"To enhance quality of life and foster economic growth by managing resources, planning, improving safety, preserving and operating infrastructure, and advancing mobility and access, all in an environmentally-sensitive manner." http://webmail.dotd.state.la.us/data2/strtpln3.nsf⟩
Michigan	"Providing the highest quality transportation services for economic benefit and improved quality of life." ⟨http://www.michigan.gov/mdot/0,1607,7-151-9623-65024--,00.html⟩
Montana	"MDT's mission is to serve the public by providing a transportation system and services that emphasize quality, safety, cost, effectiveness, economic vitality and sensitivity to the environment." ⟨http://www.mdt.state.mt.us/⟩
New Jersey	It is the mission of the New Jersey Department of Transportation to provide reliable, environmentally and socially responsible transportation and motor vehicle networks and services to support and improve the safety and mobility of people and goods in New Jersey. ⟨http://www.state.nj.us/transportation/mission.htm⟩
New York	It is the mission of the New York State Department of Transportation to ensure our customers—those who live, work and travel in New York State—have a safe, efficient, balanced and environmentally sound transportation system.⟨http://www.dot.state.ny.us/info/info.html#mission⟩
Nevada	"To efficiently plan, design, construct and maintain a safe and effective transportation system for Nevada's economic, environmental, social and intermodal needs." ⟨http://www.nevadadot.com/⟩
Oregon	"To provide a safe and efficient transportation system that supports economic opportunity and livable communities for Oregonians" http://www.odot.state.or.us/06about.htm⟩
Rhode Island	"To maintain and provide a safe, efficient, environmentally, aesthetically and culturally sensitive intermodal transportation network that offers a variety of convenient, cost-effective mobility opportunities for people and the movement of goods supporting economic development and improved quality of life." http://www.dot.state.ri.us/WebOrgz/mission.htm⟩
South Dakota	"We provide a Transportation System to satisfy diverse mobility needs while retaining concern for safety and the environment." ⟨http://www.sddot.com/geninfo_org_mission.asp⟩
Vermont	VTrans' mission is to work cooperatively to plan for and accommodate the need for movement of people and commerce in a safe, reliable, cost-effective, environmentally responsible, and equitable manner. http://www.aot.state.vt.us/MissionVision.htm⟩
West Virginia	It is the mission of the West Virginia Department of Transportation to create and maintain for the people of West Virginia, the United States and the world a multimodal and intermodal transportation system that supports the safe, effective and efficient movement of people, information and goods that enhances the opportunity for people and communities to enjoy environmentally sensitive and economically sound development. ⟨http://www.wvdot.com/11_WVDOT/11_about.htm⟩

Note: URLs accessed September to November 2003.

results of the review to identify basic frameworks that characterize the current thinking on sustainability in transportation (and other infrastructure) systems, as well as appropriate indicators and metrics for measuring progress toward sustainability. Finally, the authors discuss the findings of the reviews and their implications for future progress in addressing transportation system sustainability in education, research and practice.

Definitions of Transport Sustainability

Sixteen practitioner and research initiatives on transportation sustainability were reviewed to determine the current definitions, indicators and metrics being used to address transportation system sustainability. The initiatives include several national or international level studies undertaken by different organizations. Table 2 provides an overview of these initiatives through a summary of their objectives, expected outcomes, and funding sources, as well as their respective definitions of transportation system sustainability. The initiatives include two national studies in the United States, seven national studies in Canada, two worldwide-level studies, three European studies with an international focus, and other studies conducted in the United Kingdom and New Zealand. A majority of the initiatives are taking place in Europe and Canada. The common goals of these initiatives are to develop appropriate indicators for measuring sustainability in terms of particular needs identified and captured in unique definitions of sustainability. The Sustainable Transportation Performance Indicator project of the Center for Sustainable Transportation (CST) in Canada, for example, has conducted relatively extensive literature reviews and stakeholder involvement programs over an extended period of time to develop an appropriate definition and system of indicators and metrics.

As Table 2 shows, the initiatives reveal that there is no standard definition for transportation system sustainability. Thus, the final outputs of the studies, indicators and metrics, tend to be based on the unique definitions of sustainability adopted, and hence tend to have different emphases—much like the different foci of DOT mission statements with respect to sustainability (see Table 1). These studies therefore reinforce the idea that defining transportation sustainability is a critical element in the development of indicators and metrics to assess sustainability in transportation systems.

While the definitions of sustainable transportation reveal that there is no standard way in which sustainable transportation is being considered, there seems to be a consensus that progress must occur on at least three fronts: economic development, environmental preservation, and social development (Environment Canada 1991, 2003). This three-dimensional framework for sustainability seems to be the substance of several definitions of sustainable transportation and other infrastructure systems, both in practice and in research (see Table 2, for example). The actual indicators and metrics selected for capturing progress in these three dimensions may however be different for different agencies.

Frameworks for Indicators/Metrics of Transport Sustainability

Several frameworks were found in the literature for measuring progress toward sustainability in transportation and other infrastructure systems. As with the definitions of transportation sustainability, however, a standard framework for evaluating progress toward sustainability does not exist. Similar to the existing definitions, however, common themes and dimensions are found in these frameworks. The frameworks found in the literature can be placed into three categories: (1) linkages-based frameworks, (2) impacts-based frameworks, and (3) influence-oriented frameworks. In this paper, the term "linkages-based" is used to refer to frameworks that capture relationships between the causal factors, impacts and corrective actions related to achieving sustainability. The term "Impacts-based" is used to capture frameworks that focus on the nature and extent of various kinds of impacts (e.g., economic, environmental, social) that collectively determine the sustainability of a system (without necessarily capturing causal factors and corrective actions). The term "influence-oriented" is used to capture frameworks that are developed bearing in mind the relative levels of influence that the responsible agency or organization has on various actions and/or activities that influence progress toward sustainability. In a sense, these frameworks can be viewed as being more sensitive to the existing institutional constraints for addressing transportation sustainability. The section below describes selected frameworks from the 16 initiatives (Table 2) as well as other examples from the research literature. Each of these frameworks can be placed into one of the three categories described above. In developing definitions and indicator systems, communities and agencies may also choose to adopt a process-based approach, heavily involving community representatives and other stakeholders in defining a vision for sustainability and adopting policies to achieve this vision.

Linkages-Based Frameworks

Linkages-based frameworks for indicators and metrics capture the full range of indicators and metrics that cause particular conditions affecting sustainability, the impacts of these causes, and corrective actions that can be taken to address them. A widely used example of a linkages-based framework is the pressure-state-response (PSR) framework. Developed in Canada (Gilbert and Tanguay 2000), the framework was initially proposed by Tony Friend and David Rapport for the purpose of analyzing interactions between environmental pressures, the state of the environment, and environmental responses. The PSR framework is based on the concept of causality. It states that human activities exert pressures (such as pollution emissions or land use changes) on the environment, which can induce changes in the state of the quality and quantity of the environment (such as changes in ambient pollutant levels, habitat diversity, water flows, etc.). Society then responds to changes in pressures or state with environmental and economic policies and programs intended to prevent, reduce or mitigate pressures and/or environmental damage (OECD 1999b). Fig. 1 shows the framework of the PSR model. The model depicts that human activities exert pressures on the environment and affect the quality/quantity of life and natural resources ("state"); society responds to these changes through environmental, economic, general, and sectoral policies and though changes in awareness and behavior ("societal response"). The PSR model has the advantage of highlighting these linkages, and helping decision makers and the public to see environmental and other issues as interconnected (OECD 1999b).

Based on its wide usage, the PSR framework can be identified as a commonly agreed upon framework for indicators. Since the 1970s, the Organization for Economic Cooperation and Development (OECD) has applied an adapted version of the framework to its work on environmental reporting. The relevance and usefulness of the PSR model was reevaluated in 1989–1990 when the

Table 2. Overview of Sixteen Sustainable Transportation Initiatives

Source	Funding	Overview	Definitions and notes
USDOT (2003) Performance Rep. 2004 Performance Plan, Washington, D.C. ⟨http://www.dot.gov/PerfPlan2004/index.html⟩	USDOT	DOT has defined five strategic goal areas covering safety; mobility; economic growth and trade; human and natural environment; and national security. For each goal a set of strategic outcome goals and a number of more specific performance measures are defined for use in the annual performance planning.	The four strategic outcome goals for the environment are qualitative: (1) reduce the amount of transportation-related pollutants and greenhouse gases released; (2) reduce the adverse effects of siting, construction and operation of transportation facilities; (3) improve the sustainability and livability of communities through investments in transportation facilities; and (4) improve the natural environment and communities affected by DOT-owned facilities and equipment
USEPA (1999) Indicators of the Environmental Impacts of Transportation, updated Second Edition, Washington, D.C. ⟨http://www.epa.gov/otaq/transp/99indict.pdf⟩	USEPA	The reports attempt to provide a comprehensive overview of the full range of environmental impacts (including impacts on air, water, climate, natural habitats, and other endpoints) from transportation modes (including road, rail, air, sea), in a system-wide perspective (including impacts from production, use and scrapping of vehicles and infrastructure).	Sustainability is not mentioned. The indicators, however, included transportation impacts in the following areas: (1) Impacts on air, water, climate, natural habitats, and other endpoints (9 impacts); (2) Impacts from all transportation system modes (road, rail, air, sea); (3) Impacts from the major system elements (vehicles, infrastructure, partly fuels); and (4) Impacts from several stages of the lifecycle of each element (including production, construction, use/maintenance and disposal).
TC (2001) Sustainable development strategy 2001–2003, Ottawa, Canada.	MOST Program, Minister of Transport, Canada	The reports are structured around a set of seven challenges, broken down into 29 commitments, again broken down into targets and performance indicators. Three levels of indicators, reflecting different spheres of influence, include state level indicators (describing the state of the transportation systems in terms of sustainability), behavioral indicators (describing the behavior or activities of the actors and stakeholders whose actions matter for the state of the system), and operational indicators (describing indicators for operations and actions of Transport Canada itself).	Transport Canada has adopted a set of principles that recognize sustainable development as among the highest of departmental priorities. (1) Social principles: safety and health, access and choice, quality of life; (2) Economic principles: efficiency, cost internalization, affordability; (3) Environmental principles: pollution prevention, protection and conservation, environmental stewardship: and (4) Management principles: leadership and integration, precautionary principle, consultation and public participation, accountability ⟨http://www.tc.gc.ca/Finance/Dpr/0102/english/section_3_3_3.htm⟩
EC (1991) and (2003) Canada's Progress Towards a National Set of Environmental Indicators, State of the Environmental *Rep. No. 91-1*, Ottawa, Canada.	Minister of the Environment	This report presents 43 preliminary indicators in 18 issue areas with widespread stakeholder and media interest. This uses a modified "Pressure-State-Response" framework, and also includes a fourth category related to the nature of human activity. The structure thus encompasses four sets of issues: ecological life support systems; natural resources sustainability; human health and well-being; and pervasive influencing factors.	Progress on three fronts is presented with consensus: (1) Economic development, social development, and preservation of the environment; (2) To move towards a sustainable state; and (3) That strong linkages exist between these dimensions.

Table 2. (*Continued.*)

Source	Funding	Overview	Definitions and notes
NRTEE (2003) ESDI for Canada, Ottawa, Canada. http://www.nrtee-trnee.ca/eng/programs/ CurrentProgram/SDIndicators/ESDI-Report/ ESDI-Report-E.pdf〉	ESDI Initiative, Minister of Finance, Canada	The NRTEE has developed a draft set of sustainable transportation principles that concern access, equity, individual and community responsibility, health and safety, education and public participation, integrated planning, land and resource use, pollution prevention, and economic well-being.	Dealing mainly (but not exclusively) with the environment, the focus of the ESDI initiative is the long-term sustainability of Canada's development. In effect, it has been an effort to improve and popularize the information available to Canadians to assess intergenerational equity.
ORTEE (1995). Sustainability Indicators: The Transportation Sector, Toronto, Canada.	N/A	The report develops and assesses indicators for evaluating the impacts of possible actions or measures on the sustainability of the transportation system in Ontario. The framework adopted is based on a "criterion-influences-actions-measures" system. The conceptual model adopted is a computerized revised version of the "environment-economy linkages model."	(1) Produce outputs (emissions) at a level capable of being assimilated by the environment. (2) Have a low need for inputs of nonrenewable resources (where nonrenewable are used, their use will be for nonconsumptive investments and they will be recycled when no longer useful or needed). (3) Minimize disruption of ecological processes, land (and water area) use is also minimized as well as uses of sensitive habitats.
TAC (1999), Ottawa. Canada. 〈http://www.tac-atc.ca/english/ productsandservices/ui/exec.asp〉	N/A	TAC presents 13 principles pointing to sustainable transportation systems and related urban land use in Canada in 1993. A survey to monitor trends towards attainment of the principles can be considered as framing indicators or potential indicators to the extent that they provide appropriate quantitative responses.	Sustainable transportation is defined as follows: (1) In the natural environment: limit emissions and waste (that pollute air, soil and water) within the urban area' ability to absorb/recycle/cleanse; provide power to vehicles from renewable or inexhaustible energy sources (such as solar power in the long run); and recycle natural resources used in vehicles and infrastructure (such as steel, plastic, etc.). (2) In society: provide equity of access for people and their goods, in this generation and in all future generations; enhance human health; help support the highest quality of life compatible with available wealth; facilitate urban development at the human scale; limit noise intrusion below levels accepted by communities; and be safe for people and their property. (3) In the economy: be financially affordable in each generation; be designed and operated to maximize economic efficiency and minimize economic costs; and help support a strong, vibrant and diverse economy.
Litman, Todd; VTPI (2003). "Sustainable Transportation Indicators," Victoria, Canada 〈http://www.vtpi.org/sus-indx.pdf〉	N/A	Victoria Transport Institute presents a literature review on its approach and selection criteria for sustainable transportation indicators. They offer an alternative perspective on the selection of transport indicators by focusing on access (the ability to reach goods, services or destinations) rather than on the transportation system's ability to "move vehicles" (by measuring traffic congestion for example).	Sustainable development can be defined as. "providing for a secure and satisfying material future for everyone, in a society that is equitable, caring, and attentive to basic human needs." Sustainable transportation requires using each mode for what it does best, which typically means greater reliance on nonmotorized for local travel, increased use of public transit in urban areas, a reduction (but not elimination) of personal automobile use. Sustainable planning focuses on outcomes, such as the quality of access (the ability to obtain desired goods, services, and activities), rather than simply measuring quantity of mobility (such as travel speed or total mileage).

Table 2. (*Continued.*)

Source	Funding	Overview	Definitions and notes
CST (2003). STPI, Toronto, Canada.	Centre for Sustainable Transportation and the Government of Canada (Environment Canada and Transport Canada)	The Centre for Sustainable Transportation, Canada developed initial set of 14 STPI. They adopted four criteria to select the indicators: the indicators must be relevant to the definition, a time series, represent all of Canada, and come from a reliable source. The direction of the graph representing time seriesnumbers for each indicator shows whether progress has been made towards sustainable transportation or not.	The Centre for Sustainable Transportation, a Canadian organization, defines 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 transport mode, and supports a vibrant economy; (3) Limits emissions and waste within the planet ability to absorb them, minimizes consumption of nonrenewable resources, reuses and recycles its components, and minimizes the use of land and the production of noise.
OECD (1999a) Indicators for the Integration of Environmental Concerns into Transport Policies, Environment Directorate, Paris, France.	N/A	The document pertains to the integration of environmental concerns into transport policies through the development and use of indicators. The indicators are structured according to three themes: sectoral trends of environmental significance; environmental impacts of the transport sector; and economic linkages between transport and the environment.	The Environment Directorate of the OECD has defined environmentally sustainable transportation as: "Transportation that does not endanger public health or ecosystems and that meets needs for access consistent with (1) use of renewable resources at below their rates of regeneration; and (2) use of nonrenewable resources below the rates of development of renewable substitutes."
Segnestam, (1999). Environmental Performance Indicators (Second Edition), World Bank, Environmental Economics Series, Paper No. 71 (http://wwwds.worldbank.org/servlet/WDSServlet?pcont=details&eid=000094946_0001250540075)	World Bank Environment Dept.	The Bank's EEI Unit has prepared a manual on EPIs. This document discusses indicator frameworks, selection criteria for environmental project indicators, and issues to consider for various environmental areas.	The World Bank economist Herman Daly defined general operational principles for physically sustainable societies (not especially for the transport sector) as follows: "Their rates of use of renewable resources do not exceed their rates of regeneration. Their rates of use of nonrenewable resources do not exceed the rate at which substitutes are developed. Their rates of pollution do not exceed the assimilative capacity of the environment."
PROSPECTS (2003). Developing Sustainable Urban Land Use and Transport Strategies: Methodological Guidebook: Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems	European Commission's Energy, Environment and Sustainable Development Programme	The purpose of the report is: (1) To present a coherent but flexible general approach to planning for a sustainable urban land use/transport system, building on the logical structure; (2) To offer innovative methods of carrying out the steps of that logical structure, especially regarding appraisal of land use/transport strategies with respect to sustainability, and optimization with respect to sustainability; and (3) To provide detailed advice on a number of issues in the planning process.	A sustainable urban transport and land use system: (1) Provides access to goods and services in an efficient way for all inhabitants of the urban area; (2) Protects the environment, cultural heritage and ecosystems for the present generation; and (3).Does not endanger the opportunities of future generations to reach at least the same welfare level as those living now, including the welfare they derive from their natural environment and cultural heritage.
EEA (2002) TERM (2002)—Paving the way for EU enlargement: Indicators of transport and environment integration, Environmental Issues, Copenhagen, Denmark.	EEA, EU	The report describes the progress the EU is making towards the integration of environmental concerns into its transport policies. The aim is to monitor progress in three areas: the degree of environmental integration in the EU transport sector, progress towards transport systems that are more compatible with sustainable development, and the effectiveness of the adopted policy measures.	Sustainable development may refer to systemic characteristics such as carrying capacities of the environment, or it may refer to interrelations between economy, society and the environment.

Table 2. (*Continued.*)

Source	Funding	Overview	Definitions and notes
Baltic 21 (2000) Series No 13/98: Indicators on sustainable development in the Baltic Sea Region (An initial Set): Baltic 21 Transport Sector Report (No. 8/98). Annex 5: Indicators for Sustainable Transportation, Stockholm, Sweden ⟨http://www.ee/baltic21⟩	Ministry of Environment	Baltic 21 selects indicators according to three different types of goals and measures: (1) Indicators with regard to primary goals for sustainable transport; (2) Indicators with regard to institutions, instruments, and measures; (3) Indicators with regard to the transport system and transportation activity	The essential objective of Baltic Sea Region cooperation is the constant improvement of the living and working conditions of their peoples within the framework of sustainable development, sustainable management of natural resources, and protection of the environment." Sustainable development includes three mutually interdependent dimensions—economic, social, and environmental.
DSD (2003) Achieving a better quality of life, review of progress towards sustainable development, United Kingdom, ⟨http://www.sustainable-development.gov.uk/ar2002/pdf/ar2002.pdf⟩	DEFRA	The United Kingdom presents the ten guiding principles: (1) Putting people at the center; (2) Taking a long term perspective; (3) Taking account of costs and benefits; (4) Creating an open and supportive economic system; (5) Combatting poverty and social exclusion; (6) Respecting environmental limits; (7) The precautionary principle; (8) Using scientific knowledge; (9) Transparency, information, participation, and access to justice, and (10) Making the polluter pay.	Sustainable development is about ensuring a better quality of life for everyone, now and for generations to come. This requires meeting four key objectives at the same time in the United Kingdom and the world as a whole: (1) Social progress which recognizes the needs of everyone; (2) Effective protection of the environment; (3) Prudent use of natural resources, and (4) Maintenance of high and stable levels of economic growth and employment.
NZME (1999) Proposals for Indicators of the Environmental Effects of Transport ⟨http://www.mfe.govt.nz/publications/ser/transport-proposals-full-jun99.pdf⟩	NZME	The main purpose of the document is to provide the basis for agreement on the use of a core set of indicators to measure the environmental effects of transport. The components of the framework are these: (1) Root causes of transport activity; (2) Indirect pressures; (3) Direct pressures; and (4) State or effects indicators	Supposed indicators are balanced between indicators of direct (for example, atmospheric emissions) and indirect (for example, development density, travel demand) transport pressures on the environment. The PSR framework was used for developing indicators.

Note: USDOT=United States Department of Transportation; USEPA=United States Environmental protection Agency; TC=Transport Canada; EC=Environmental Canada; MOST=moving on sustainable transportation; NRTEE=National Round Table on the Environment and the Economy; ESDI=environmental sustainable development indicators; ORTEE=Ontario Roundtable on the Environment and the Economy; N/A=not available; TAC=Transportation Association of Canada; VTPI=Victoria Transport Policy Institute; CST=Centre for Sustainable Transportation; STPI=sustainable transportation performance indicators; OECD=Organization for Economic Cooperation and Development; EEI=environmental economic indicators; EPI=environmental performance indicators; PROSPECT =procedures for recommending optimal sustainable planning of European city tranport systems; EEA=European Environment Agency; TERM=transport and environment reporting mechanism; EU =European Union; DSD=Department of Sustainable Development; DEFRA=Department for Environment, Food and Rural Affairs; NZME=New Zealand Ministry of the Environment; and PSR=pressure state response.

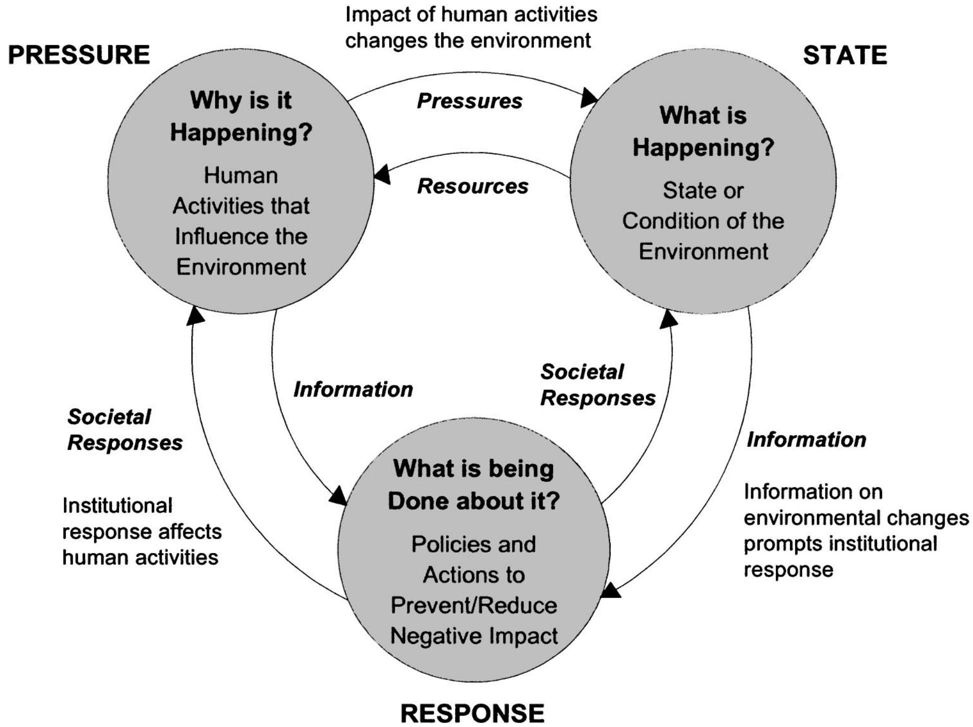

Fig. 1. Pressure-state-response model (adapted from OECD 1999b)

OECD initiated its work on environmental indicators. In developing a core set of environmental indicators, OECD countries agreed that the PSR model was a robust and useful framework and should continue to be used in the Organization's work on environmental data and indicators (OECD 1999b).

The OECD's indicator development is thus based on a modified version of the PSR model, adapted to take into account specificities in the transport sector. The model has been modified to distinguish between two categories of pressures: driving forces and pressures, and two categories of state: state and impact. The modified model is called drivers-pressures-state-impact-responses (DPSIR). The DPSIR model has been adopted as the most appropriate way to structure environmental information by most member states of the European Union (EU) and by international organizations dealing with environmental information, including the European Environmental Agency and EUROSTAT, the statistical office for the European Communities (Gilbert and Tanguay 2000).

Another example of the linkages framework is seen in the work of The Ontario Round Table on Environment and Economy (ORTEE). The ORTEE has adopted a framework based on a "criterion-influences-actions-measures" system. The conceptual model adopted was a computerized revised version of the "environment-economy linkages model" developed by Hickling Corporation and Econometrics Research Limited in 1993. The system, similar to the PSR framework, is really a "model" of the relationships among sustainability criteria, the output being the set of indicators. The model connects environmental discharge and resource use, on a country basis, to a regionalized input–output model of the Ontario economy. A selected criterion, such as carbon dioxide emissions, for example, can be deconstructed into a number of influences (e.g., persons per vehicle, vehicle kilometers traveled, etc.). These influences can trigger different actions by policy makers such as the establishment of new transit lines or car pool databases. These actions can, in turn, be facilitated by different policy measures (Gilbert and Tanguay 2000).

Indicator systems developed based on this concept can help agencies to develop a better understanding of the actions and activities that are influencing the state of the system, and appropriate responses for addressing them, both for the agency and other stakeholders of the system.

Impacts-Based Frameworks

Impacts-based frameworks are focused on the impacts of various actions on the sustainability of the particular system under consideration. A common impacts-based framework is the three-dimensional framework of indicators based on economic, environmental, and social impacts. The tripartite framework, as it is known in some of the research literature (see, for example, Ashley and Hopkinson 2002) has also been used in evaluating transportation system sustainability. For example, the evaluation framework proposed for sustainable urban transportation systems by the Transportation Association of Canada (TAC) has three dimensions related to the economy, natural environment, and society. In the natural environment, the system is expected to limit emissions and waste; in society, it is expected to provide equity of access for people and their goods, enhance human health, and support the highest quality of life compatible with available wealth; and, in the economy, it is expected to help support a strong, vibrant and diverse economy (TAC 1999). The Victoria Transport Policy Institute (VTPI) uses a similar framework for sustainable transportation indicators. Although VTPI has a stronger focus on transportation and land use interactions, their comprehensive list of sustainable transportation indicators are also organized according to economic, social, and environmental impacts (Litman 2003).

The tripartite framework is also found in the research literature for addressing sustainability in other types of civil infrastructure systems. Ashley and Hopkinson (2002), for example, present a tripartite framework as key groups of indicators to characterize

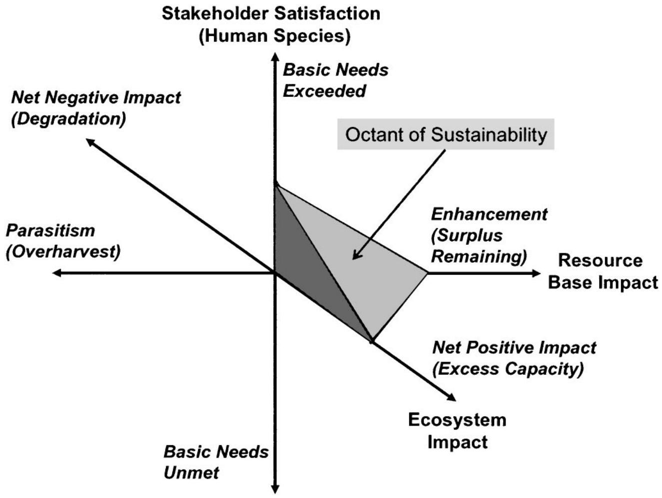

Fig. 2. Triaxial representation of technological sustainability (adapted from Pearce and Vanegas 2002, used with permission)

alternative measures of sustainable development in decision making for water and sewer systems. For each of the three dimensions: economic, ecological, and socio-political, important aspects are identified and then measurement methods and measures are developed for each aspect. For example, growth, equity and efficiency are identified as important aspects of economic sustainability; and methods such as the Green Gross National Product and resource accounting are identified for measuring progress in these domains, using such relevant metrics as money and energy per unit of expenditure. Balkema et al. (2002) also present a tripartite framework for measuring sustainable technology in wastewater treatment systems based on the nature and extent of the interaction of technology with the economic, physical, and sociocultural environment.

Using a similar paradigm, Pearce and Vanegas (2002) discuss the thermodynamic foundations of sustainability and develop three parameters for measuring technological sustainability in decision making for building infrastructure. The thermodynamic foundations of sustainability assume that the earth is a constrained open system (virtually closed) with solar radiation as an input and waste heat as an output. While there is no net loss of matter or energy, there is degradation of energy from higher to lower forms, i.e., entropy. Entropy results from consumption and is offset by natural ecosystems in the form of photosynthesis (Pearce 2000). Thus, from a thermodynamic standpoint, the two objectives necessary to maintain sustainability of the global earth system are: (1) to minimize the consumption of matter and energy and (2) to minimize negative impacts to natural ecosystems, as they are the only mechanism for offsetting the entropy resulting from consumption. These concepts of consumption and environmental impact minimization can extended to the operation and management of built systems, where the objectives become exploring investment options that achieve comparable levels of system performance with a net reduction in system inputs, e.g., the total energy consumed per mile of travel in a metropolitan transportation system, and outputs, e.g., total amount of pollutants emitted by the system in a specified period. Pearce and Vanegas (2002) extend this concept to develop the following three dimensions for measuring technological sustainability: (1) the level of stakeholder satisfaction, (2) the resource base impact, and (3) the ecosystem impact. Fig. 2 shows the triaxial representation of the parameters for technological sustainability. The figure illustrates that in selecting among alternatives to move building (and other infrastructure) systems toward sustainability, the alternatives should satisfy stakeholders (i.e., they should not necessarily be optimal but satisficing with regard to stakeholder desires), while having a net positive or neutral impact on the resource base and the natural environment (i.e., they results of decisions should lie in the "octant of sustainability").

Also using a similar paradigm, Rijsberman and van de Ven (2000) discuss four basic approaches to sustainability, which are influenced by four aspects: people, norms, values, and the environment. In this framework, two contrasting attitudes toward the relationship of people–environment can be distinguished. In a people-driven approach, people and their desires, needs, and objectives are the driving forces behind the perception of sustainable development. Environment-driven approaches, on the other hand, state that the seriousness and extent of environmental problems should be established objectively from nature. The way in which this relationship or interaction is evaluated can also be distinguished by two contrasting approaches: a quantitative approach based on norms, and a qualitative approach based on values. Various combinations of these four aspects result in four basic approaches: (1) norms and environment: capacity approach; (2) norms and people: ratiocentric approach; (3) values and people: sociocentric approach; and (4) values and environment: ecocentric approach. The carrying capacity approach is a normative approach that focuses on the carrying capacity of supporting ecosystems or the environment and develops target values that are sustainable levels of environmental stress within the existing carrying capacities of various norms, e.g., air quality, water quality, etc. The ecocentric approach views sustainability as ecologically feasible. The objectives are not met by trying to meet stringent norms but by creating positive conditions for desired development. It is more of a proactive than retroactive approach. In the ratiocentric approach, choices are made based on the evaluation of multiple criteria in the present situation, considering the objectives of decision making, and evaluating all interests involved. In a sociocentric approach, the interests and opinions of stakeholders are central, and priorities are set in an interactive process. This is a qualitative approach that emphasizes participation in the objectives of decision making and the decision making itself. These four approaches point out various emphases that can be made in sustainability planning; depending on the existing decision-making context; institutional constraints; data availability; relative levels of stakeholder interest and involvement; presence or absence of executives and/or political leaders who are champions of sustainability; and other relevant resources.

Influence-Oriented Frameworks

Influence-oriented frameworks categorize indicators by the level of influence and control that the responsible agency has with respect to the various factors that cause or otherwise influence the sustainability of the infrastructure system under consideration. Transport Canada (2001) has developed an important tiered framework of performance indicators that reflects the relative level of influence and control that the agency has with respect to making progress toward sustainability. The framework has three levels of indicators: state level indicators, behavioral indicators, and operational indicators. State level indicators or state-of-the-system indicators describe the state of the transportation system in terms of sustainability. This level of indicators addresses the overall vision or goal of activities for obtaining a sustainable transportation system and measures how well the system is performing relative to this vision. Behavioral indicators, on the other hand, are related to the behavior or activities of the actors and stakeholders whose actions influence the state of the system. Stakeholders include transportation infrastructure and service providers, system operators, political, and other decision-makers, and the general public. This level of indicators is relates to the mission of Transport Canada and captures the extent to which the agency's activities are resulting in behavioral and activity change within the system, which then impacts the overall goals for the system. Operational indicators are described as indicators for operations and actions of Transport Canada itself. This level of indicators is related to the agency's mandate, i.e., where it has clear responsibilities. As such, Transport Canada's indicator system recognizes explicitly that the agency has varied degrees of control and influence over different activities and aspects that influence transportation system sustainability. The indicator system explicitly recognizes that the agency has only indirect influence over the state level indicators, direct influence over the behavioral indicators, and direct control over the operational indicators (Gudmundsson 2000).

Process-Based or Stakeholder Approaches

A process-based approach to sustainability acknowledges that addressing sustainability must be done through a planning process which effectively engages stakeholders in creating their vision of sustainability. Process-based frameworks are based on a decision-making process for developing consensus, involving all the representatives from various constituencies within the community (Environmental Defense 1999). Initiatives such as the DOE "Ten Steps to Sustainability" outline a process for engaging communities/stakeholders in thinking about and articulating their vision for sustainability, developing a roadmap for reaching this vision, developing indicators to measure progress toward this vision, and incorporating sustainability into local policy to promote attainment of sustainability (USDOE). Process-based mechanisms are crucial for articulating the right vision for a community (at the local, state, national or multinational levels). They are also potentially effective mechanisms for educating stakeholders and the general public about sustainability and promoting progress toward consensual sustainability goals through collective behavioral change. From an agency viewpoint, this implies that there is tremendous value in viewing public involvement as a critical component of sustainability planning.

Balance in Frameworks

It is important that agencies give thought to defining an appropriate balance of input (causative) versus outcome (impact) measures. Gudmundsson's (2000) evaluation of transportation sustainability initiatives in Europe and North America revealed seemingly different foci with respect to achieving transport sustainability in Europe and North America. Table 3 summarizes the foci of the different initiatives. The EU had set up seven policy questions, Transport Canada (TC) had established seven challenges, and the United States Department of Transportation (USDOT) had established five strategic outcome goals. Gudmundsson found Europe's approach to cover a wider range of surrounding policy issues (that would affect or influence progress toward transport sustainability), while TC and the USDOT approaches more or less concentrated on management challenges and internal responsibilities. He concluded that the North American approach seems to be reaching "outwards" for more results or outcome-oriented performance goals, while the European approach seemed to be reaching "inwards" for policy-related response or input. An appropriate balance of input and outcome measures, distributed appropriately across the various responsible agencies in a manner that is consistent with their different missions and spheres of influence, could be more effective for addressing sustainability.

Synthesis of Indicator Frameworks

The indicator frameworks discussed above can be helpful in various ways to agencies that are contemplating including sustainability in their mission statements, revisions to their mission statements or the development of indicators and metrics to evaluate progress toward predefined goals. Such frameworks have been used by various agencies to develop indicator and metric systems for addressing sustainability. For example, Canada's CST initial plan was to develop indicators that added quantitative flesh to its definition of sustainable transportation. This was achieved by deconstructing the definition of sustainable transportation into numerous elements, quantifying each element as a target, and fashioning for each target one or more indicators that represent movement toward or away from the target. Canada's CST developed three levels of STPIs, a single composite indicator with descriptive indicators that reflect the components of the single indicator, and explanatory indicators that enhance understanding of transport activity and its impacts. Descriptive indicators (similar to state indicators in the PSR framework) were developed to represent the effects of transportation and whether these effects were changing in directions consistent with sustainability. Explanatory indicators (similar to pressure indicators in the PSR framework) were developed to represent contributory factors that can help explain changes in descriptive indicators and that contribute to policy formulation (CST 2003).

Agencies can also combine the frameworks to help them develop more comprehensive indicator systems. For example, an indicator system that includes all the three elements: i.e., one that is impacts-based, linkages-based, and level-of-influence-based, would help an agency to understand the most effective actions they can take (linkages element) to make progress in selected domains (impacts element, e.g., safety, economics, environment, etc.,) related to their mission (level of influence element). Such a comprehensive framework could also be useful for thinking about an appropriate balance of input (or inward-looking) indicators versus output (or outward-looking) indicators (as captured in Table 3). Fig. 3 illustrates this concept of a unified framework for developing indicator and metric systems. The unified framework identifies three attributes for guiding the development of indicator systems: (1) what level of influence does the agency have over this indicator (x axis)? (2) Is the indicator an input or output of the system (y axis)? (3) What is the relative level of impact of this indicator on achieving system sustainability (z axis)? In this unified paradigm, an agency, such as one of the DOTs with a mission to develop a sustainable transportation system (see Table 1), could focus on identifying the current and predicted areas of highest impact relative to creating a sustainable transportation system, identify causal factors (inputs, y^+ axis) that have the most significant effect on these high impact areas (z^+ axis), narrow down on the causal factors that are within its domain of highest influence or control (related to its mission) (x^+ axis), and then begin to develop policies, planning procedures, databases, and analysis tools to address these areas. Such an approach could also be used in defining transportation system sustainability in a manner that is

Table 3. Input and Output-Oriented Systems for Achieving Sustainable Transportation (adapted from Gudmundsson 2000)

EU 2000 Transport and environment reporting mechanism "7 policy questions"	Transport Canada 2000 sustainable development strategy "7 challenges"	USDOT 1997 Strategic goals-Human and natural environment "4 strategic outcome goals for the environment"
Is the environmental performance of the transport sector improving?	Reducing pollution of land and water	Reduce the amount of transportation-related gases released
	Reducing air emissions	
		Reduce the adverse effects ofsiting, construction, and operation of transportation facilities
Are we getting better at managing transport demand and at improving the modal split?	—	—
Are spatial and transport planning becoming better coordinated so as to the needs of access?	—	Improve the sustainability and livability of communities through investments in transportation facilities
Are we optimizing the use of existing transport infrastructure capacity and moving towards a better-balanced intermodal transport system?	Promoting a more efficient transportation system	—
Are we moving towards a fairer and more efficient pricing system, which ensures that external costs are recovered?	—	—
How rapidly are improved technologies being implemented and how efficiently are vehicles being used?	Promoting improved technology for sustainable transportation	—
How effectively are environmental management and monitoring tools being used to support policy and decision making?	Improving environmental management in the transportation sector Developing tools for better decisions Improving education and awareness of sustainable transportation	Improve the natural environment and communities affected by DOT-owned facilities and equipment

Note: EU=European Union; and USDOT=United States Department of Transportation.

most relevant to an agency and its jurisdiction's present and future needs. Using these frameworks, in the context of a process/stakeholder-based approach, could substantively improve effectiveness and efficiency in addressing sustainability in infrastructure systems, as progress is simultaneously being made with the institutional reform, data and analytical capabilities, and education initiatives necessary to address sustainability in the longer term.

Indicators and Metrics of Transportation Sustainability

All the indicators and metrics being used in the 16 initiatives may be classified as one of the following: transportation-related (including safety), economic, environmental, and socio-cultural/equity-related. Table 4 provides a comprehensive list of the indicators and metrics being used in the 16 initiatives to evaluate progress toward sustainability. In general, the main indicators being used to address transportation sustainability can be inferred from this table. The indicators and metrics are sorted by the relative frequencies with which they appear in the indicator systems of the 16 initiatives.

From Table 4, it is clear that transport-related and environmental indicators seem to be the most widely used indicators for sustainable transportation. The transport-related indicators include safety indicators. About half of the initiatives have safety indicators. These indicators are largely focused on outcome measures such as injury or fatality crashes. All the 16 initiatives have environmental indicators. Environmental indicators that seem to be in higher use are linked to vehicle emissions and fuel consumption. Common environmental indictors include emissions of various air pollutants, especially green house gases such as carbon dioxide, nitrogen oxides, and volatile organic compounds. Fuel consumption also appears to be a common environmental indicator. Economic measures, largely captured as per capita indicators, are seen in only few of the initiatives. Canada's ORTEE and TAC, the World Bank, Europe's PROSPECTS (2003), and New Zealand

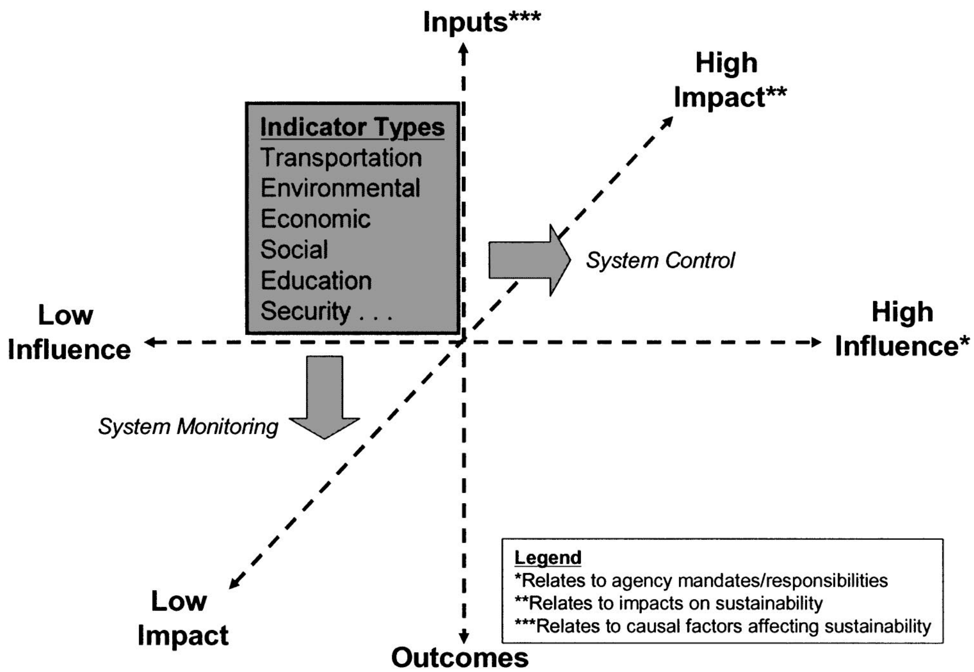

Fig. 3. Unified framework for developing indicator systems for infrastructure system sustainability

are the only initiatives with any economic indicators. Sociocultural and equity-related indicators do not seem to be in wide use either. Canada's ORTEE, VTPI, PROSPECTS, the Baltic States, and New Zealand are the only initiatives with sociocultural/equity-related indicators, and even so each initiative has very few indicators in this domain. Thus, the synthesis of indicators in Table 4 would seem to suggest that sustainable transportation is largely being captured more by transportation effectiveness and efficiency indicators (including safety indicators) and environmental indicators; and, to a lesser extent by economic and social indicators. In addition, there are significant differences in the balance of input and output measures being used in the different domains, i.e., environmental versus economics. While analysis of the adequacy of the different indicator systems is beyond the scope of this paper, the point must be made that any analysis of these indicator systems cannot be conducted outside the context of their relative adequacy for achieving the visions that they were created to support.

Findings and Implications

The review and synthesis of the literature on sustainability in transportation and other infrastructure systems leads to a number of important findings. First of all, it is clear that sustainability in infrastructure systems planning and provision is an issue of growing importance based on ongoing activity in practice and research to define and measure sustainability in infrastructure systems. Second, while there are no standard definitions for sustainable transportation systems, there is consensus that sustainable transportation must impact at least three areas: the economy, the environment, and overall social well-being. Third, while there is no standard framework for evaluating progress toward sustainability, it is clear that the existing and emerging evaluation frameworks try to do at least one of the following: (1) capture the causal relationships that lead to progress toward or deviation away from sustainability; (2) capture 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) capture the level of influence or control that the responsible agencies have over the causal factors of sustainability. In addition, a stakeholder or process-based approach seems critical in sustainability planning for capturing the visions and values of different communities at various sociopolitical levels (local, state, national, and multinational). Fourth, the present status of addressing sustainability in transportation planning and provision seems to indicate a higher focus on the effectiveness and efficiency of transportation systems planning and provision as well as the resulting environmental impacts, and less of a focus on economic and social impacts.

Generally absent in the 16 initiatives reviewed are considerations of education initiatives to promote awareness of the importance, benefits, and challenges of moving toward sustainability. Public education is clearly an integral component of any systematic initiative to move toward sustainability. Sustainability planning initiatives that are process-based with heavy involvement of stakeholders naturally have an education component that may not require measurement. Nonetheless, there is arguably value in viewing education as a tool in itself for achieving sustainability, in which case there would be value in developing specific education initiatives to achieve certain goals, and measuring how well these initiatives are achieving such predetermined goals. Education is a potentially powerful tool for cultivating collective behaviors that support sustainability. Also generally absent from the indicator systems are factors influencing or otherwise impacting the security of transportation and other infrastructure systems, also a critical element of infrastructure system sustainability. Security is used here to refer to the vulnerability and survivability of infrastructure systems in various attack scenarios.

It also worth noting that not all the indicator systems have both input and output indicators in every domain of indicators, e.g., safety, economics, etc. Where any particular domain is heavily output-oriented, this is an indication that little is being done to track and influence actual actions and/or activities that affect sustainability in this domain. If such actions and activities were out-

Table 4. Indicators and Metrics for Sustainable Transportation Systems (Sixteen Initiatives)

	US DOT	US EPA	Trans Canada	EC[3]	NRTEE[4]	ORTEE[5]	TAC[6]	VTPI[7]	CST[8]	OECD	World Bank	PROSPECTS[9]	EEA[10]	Baltic	UK	New Zealand
Economic																
Population density (persons/ha)						■	■									■
Economic efficiency						■						■				
Employment						■	■									
Accessibility measures												■				
Public expenditure												■				
Growth potential												■				
Green GDP						■										
GDP per unit of energy use											■					
Tax revenues						■										
Implementation of internalisation instruments													■			
Employment-to-population ratio in Central area							■									
Transportation-related																
Length of railways and main roads, Parking facility								■	■	■				■	■	■
Passenger-kilometres (by mode, purpose)				■					■		■		■		■	■
Freight tonne-kilometres (by mode, purpose)									■		■		■		■	■
Total kilometres driven(VMT)				■	■		■		■							■
Unit sales of cars/trucks (Auto Use per capita)					■					■	■			■		
∑ Traffic volumes of road, rail, air, sea (vehicle-kilometres)									■		■			■		
Public transit and automobile use				■			■	■								
Avg. home-work trip distance/time (by purpose)							■			■			■			
Portion of transportation-related costs paid by public funding (Subsidy)								■		■			■			
∑ Total passenger and cargo turnover by air, ship, road, rail; mode shifts											■			■		
Per-capita gas consumption vs. urban density					■		■									
Mixed land use						■		■								
Average. portion of Household transportation expenditures								■	■							
Length of public transport network										■				■		
Extent and density of transport Infrastructure										■	■					
Land Area Occupied by Roadways/Transportation Infrastructure		■											■			
(Morning peak) Auto occupancy to/from CBD							■						■			

3 Environment Canada
4 National Round Table on Environment and Economy
5 Ontario Round Table on Environment and Economy
6 Transportation Association of Canada
7 Victoria Transport Policy Institute
8 Center for Sustainable Transportation, Canada
9 Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems
10 European Environment Agency

Table 4. (*Continued.*)

	US DOT	US EPA	Trans Canada	EC[3]	NRTEE[4]	ORTEE[5]	TAC[6]	VTPI[7]	CST[8]	OECD	World Bank	PROS PECTS[9]	EEA[10]	Baltic	UK	New Zealand
∑ Total investment in maintenance costs wrt road/rail/harbor/air infra													■	■		
Growth/trend of gasoline prices and share of taxes in diesel fuel and gasoline prices (%)										■			■			
Real changes in the cost of transport													■		■	
Annual transit ridership	■						■									
Vehicle fleet composition													■			■
Transport intensity (passenger or ton-kilometres/GDP)										■						
Aircraft departures											■					
Capacity of transport infrastructure networks, by mode and by type of and services infrastructure													■			
Short journeys per person per year by mode															■	
Commute cost						■										
Commute time						■										
Total amount of external costs by transport mode													■			
Total light-duty vehicles					■											
Motor vehicles											■					
Two-wheel vehicles											■					
% of low emission vehicles purchased of total annual vehicles purchased			■													
Diesel locomotives available											■					
Non-auto trips (% of urban trips not by automobile)						■										
Trips with 2 or more modes						■										
Arterial lane-km							■									
Expressway lane-km							■									
HOV lane-km							■									
Morning peak period transit seat-km							■									
24-h transit seat-km							■									
Off-street parking spaces per employee in CBD							■									
Morning peak transit mode share to/from CBD							■									
Morning peak auto mode share to/from CBD							■									
24-h person trips							■									
24-h arterial auto vehicle-km per capita							■									
Road Utilization Index (RUI) (vehicle-km/lane-km)							■									
Total road expenditures							■									
Total transit expenditures							■									
Farebox revenue/operating and maintenance budget							■									
Average amount of residents' time devoted to non-recreational travel								■								
Quality of public transit service, integration with other modes								■								
Public transport performance												■				
Quality of delivery services								■								
Quality of mobility services for residents with special mobility needs								■								

Table 4. (*Continued.*)

	US DOT	US EPA	Trans Canada	EC[3]	NRTEE[4]	ORTEE[5]	TAC[6]	VTPI[7]	CST[8]	OECD	World Bank	PROS PECTS[9]	EEA[10]	Baltic	UK	New Zealand
Share of areas larger than 100 km2 not separated by motorways														■		
Change in level of road congestion over time																■
Usual mode of transport for journey to work																■
Gas and diesel fuel prices at the pump					■											
Expenditure on personal mobility per person by income group													■			
Relative transit cost (Avg. transit fare to Avg. gas cost)									■							
Load factors for freight transport (LDV, HDV)													■			
% travel meeting pavement performance standards	■															
Of total annual urban-area travel, % occurs in congested conditions	■															
Environmental																
CO2 emissions (by mode)		■	■	■		■	■			■	■		■	■		
Greenhouse gas emissions	■			■	■				■		■		■		■	
Fossil fuel consumption				■			■		■	■			■	■		
Per-capita use of transportation energy	■				■		■	■	■					■		
Emissions of air pollutants (from Transportation Vehicle and Equipment Manufacturing)	■	■						■		■			■	■		
NOX emissions (by mode)		■							■	■			■	■	■	
VOCs emissions		■							■				■	■		
Main land use/Urban land use		■				■						■				
Fossil fuel use by auto		■		■						■						
Waste/Recycling		■	■										■			
CO emissions		■							■						■	
Emission intensity									■				■			
Noise level/cost		■										■		■		
Green area									■			■				
Toxic substances in urban air: benzene/ozone		■		■										■		
Fuel efficiency of new auto				■						■						
E-index (Per capita energy consumption)				■		■					■					
Non-fossil fuel use (Alternative fuel)						■							■			
Wetland losses and creation	■	■														
Hazardous materials incidents	■	■														
Maritime Oil spills	■	■											■			
Overall energy efficiency for passenger and freight transport				■									■			
CO2 cost[11]												■				
SO2 emissions		■							■							
CH4 emissions		■									■					
Black smoke emissions															■	
Lead emissions		■													■	
Air pollution cost												■				
Chlorofluorocarbons and stratospheric ozone depletion		■		■												

[11] Emissions in tones weighted by shadow cost of national CO_2 target

Table 4. (*Continued.*)

	US DOT	US EPA	Trans Canada	EC[3]	NRTEE[4]	ORTEE[5]	TAC[6]	VTPI[7]	CST[8]	OECD	World Bank	PROS PECTS[9]	EEA[10]	Baltic	UK	New Zealand
Urban sprawl												■				
Fragmentation/Particles/ Volatile organic compounds		■		■										■		
Vulnerable areas												■				
Worldwide major natural disasters					■											
Ecological footprint						■										
Demotechnic Index						■										
Percentage of reused or recycled parts of different types of end-of-life vehicles														■		
Number of Motor Vehicles Scrapped Annually, Disposition of Scrap Tires		■														
Lead Acid Batteries in Municipal Solid Waste Streams		■														
∑ Investments dedicated to environmental protection														■		
Percentage of arterial roads and state highways with appropriate levels of storm water treatment																■
Sediment loads in streams (pressure indicator)																■
Change in criteria pollutant emissions compared to vehicle travel 1940-1997		■														
No. of animal/wildlife collisions		■														
Water Quality		■														
Fuel Tank Lickage		■														
% of tanks in compliance with Guidelines			■													
Mobile Source Contribution to Hazardous Air Pollution Inventories		■														
Toxic Chemicals Released from Ship- and Boat Building & Repairing Facilities		■														
Average monthly ambient air concentrations in capital/town											■					
Fisheries Protection-Compliance rate with Federal fisheries regulations	■															
Environmental costs and liabilities as reported to Treasury Board			■													
Number of contaminated sites undergoing remediation or risk management			■													
Fragmentation of ecosystems and habitats		■											■			
Percentage of strictly protected area				■												
Change in emissions of toxic substances variable				■												
Change in sulphur dioxide emissions (Acid Rain)		■		■												
Per capita water use				■												
Municipal wastewater treatment improvement				■												
Percentage of ecozone with strictly protected forest area				■												
Reduction in number of bare-soil days on				■												

Table 4. (*Continued.*)

	US DOT	US EPA	Trans Canada	EC[3]	NRTEE[4]	ORTEE[5]	TAC[6]	VTPI[7]	CST[8]	OECD	World Bank	PROS PECTS[9]	EEA[10]	Baltic	UK	New Zealand
agricultural land				■												
Per capita non-hazardous solid waste generation				■												
Dredging and impacts to aquatic resources		■														
Introduction of non-native species		■														
Impervious surfaces		■														
Releases of deicing chemicals, cleaning fluids, and wastewater		■														
Solid waste (Motor vehicle scrappage, motor oil, tires, etc.)		■														
Safety-oriented																
Deaths and injuries (Safety risks: injuries or fatalities per vkt, per vehicle)						■	■	■	■	■			■	■		
Accidents											■	■	■			
Accident cost												■				
Vulnerable user accident												■				
Medical costs attributed to transportation								■								
Number of cases of serious pollution or health effects														■		
Social-cultural/ Equity-related																
Residential population exposed to outside airport noise	■	■											■			■
Accessibility for those without a car								■				■	■			
Residential population exposed to outside road traffic noise		■											■			■
Avg. No. of major services within walking distance of residents and Avg. walking distance between residences and public services								■		■				■		
% increase in environmental awareness, as measured by surveys or testing			■										■			
Local activity												■				
Quality of transit wrt mobility impaired												■				
Income inequality												■				
Equity impact tables												■				
User benefit inequality												■				
Benefits by zone												■				
Taxpayer' money												■				
Crime						■										
Community disruption						■										
Distribution Inequality Index						■										
Vehicle access						■										
Quality of pedestrian and bicycle environment								■								
Affordability of public transit service by lower income residents								■								

Table 4. (*Continued.*)

	US DOT	US EPA	Trans Canada	EC[3]	NRTEE[4]	ORTEE[5]	TAC[6]	VTPI[7]	CST[8]	OECD	World Bank	PROSPECTS[9]	EEA[10]	Baltic	UK	New Zealand
Proportion of residents with public transit service within 500 metres	■															
Residents' participation in transportation and land-use decision making								■								
Consumer perception of satisfaction with air quality		■														
Environmental justice-Environmental justice cases that remain unresolved over one year	■															
% of Environmental emergency plans in place (% of plans up to date)			■													
Population exposed to exceedances of EU air quality standards for PM10, NO2, benzene, ozone, lead and CO													■			
Proximity of transport infrastructure to designated areas													■			
Regional access to markets: the ease of reaching economically important assets by various modes													■			
Extent of Performing Transport/ Environment Integration Management													■			
% of bus fleets/key rail station with ADA compliant	■															
Access to basic service										■						

side the responsibility or mission of the responsible agency, then it would seem logical that the agency has chosen to focus only on outputs in this domain, in the short term. Otherwise, there would be value in identifying and including input indicators and defining associated policies and procedures to directly or indirectly affect progress toward sustainability.

It is also generally the case that the indicator systems do not attempt to separate out higher-impact indicators and metrics from lower-impact ones. A recent paper by Banister and Pucher (2003) identifies and discusses critical-impact areas for attaining sustainability in transportation systems. Beginning to prioritize factors for evaluating sustainability according to their relative potential for moving jurisdictions forward toward sustainability would be a useful step forward in the development of systematic approaches for evaluating sustainability in infrastructure systems.

Other Relevant Issues

Many debates about the merits of sustainability hinge on the burden of proof of a sustainable system. In essence, if there is no consensus on what would constitute a sustainable system state, how can one plan for such a system? Furthermore, uncertainties that characterize long range planning (e.g., data forecasting, technological innovation, and sociopolitical upheavals, etc.) introduce risks that would make it more difficult to plan for sustainability. To compound these issues is the question of whether a "sustainable transportation system" can exist in isolation of the numerous other systems with which it interacts, and if not, how one then goes about delineating the boundaries of such a system. Scenario planning and the concept of satisficing (as opposed to optimizing) together present a conceptual platform on which to address these issues. Herbert Simon made a strong impact on the field of organizational decision making by demonstrating that far from making optimal choices, organizations often search through the set of possible alternatives until they find one that satisfies an aspiration level, and then terminate their search (Dawes 1988). Scenario planning, traditionally used in business-strategic planning, helps organizations judge how decisions made today will be effective in an uncertain future. Hence, rather than forecasting conditions for an uncertain future, several plausible future scenarios are considered and the robustness of various decisions under these scenarios are evaluated (Schwartz 1996). The benefits of scenario planning are being considered for regional strategic transportation planning purposes (see for example Zegras et al. 2004) as they address uncertainties better than traditional planning methods. Coupled with the concept of satisficing, scenario planning can serve as a point of departure for addressing the issues of burden of proof and uncertainty in sustainability planning. The issue of defining the boundaries of the system could also be addressed through the scenarios that are depicted. In other words, the extent to which land use policies, technological innovations, and other causal factors and systems are incorporated in the planning will be left to the jurisdiction of the planner as s/he develops alternative future scenarios.

Two types of questions emerge in practical considerations for addressing sustainability in transportation and other infrastructure systems: (1) what is the right vision for a particular community and (2) how can this community most effectively achieve this vision? (The latter includes the development of policies with teeth, education initiatives, and other tools to promote or cultivate movement toward the vision; and the effective measurement of progress toward this vision). Thus, "do we have the right vision?" and "do we have the right measurement system for attaining this vision?" are both critical questions that any entity interested in addressing sustainability must answer. Inherent in these questions are issues of growth (used here to depict getting bigger) versus development (used here to depict getting better). The effectiveness of an indicator/metric system cannot be evaluated outside the context of how well it is able to measure the vision for which it was developed. Information quality attributes such as data completeness, accuracy, and precision also cannot be evaluated outside the context of these broader and more fundamental questions.

Summary and Conclusions

Given the growing interest in addressing infrastructure sustainability, the objectives of this paper were to evaluate definitions, indicators, and metrics being used to address sustainability in transportation (and other infrastructure) systems, in order to characterize the current thinking on what constitutes infrastructure sustainability and how it is measured. Sixteen sustainability initiatives around the world were reviewed, together with selected sustainability initiatives of other civil infrastructure systems found in the research literature. The findings indicate that while there is no standard definition for transportation sustainability, there seems to be emerging consensus that, in order to be effective, it must include impacts on the economy, environment, and social well-being; it must address the causes of sustainable or nonsustainable trends; it must consider the relative levels of influence that oversight agencies have with respect to implementing policies and procedures that impact sustainability; it must include an appropriate balance of input and output measures; and it must have a strong stakeholder component. The existing indicator systems reveal that operationally, transportation sustainability is largely being measured by transportation system effectiveness and efficiency as well as the environmental impacts of the system. In general, the indicator systems do not seem to be capturing the important role of education as a critical tool for moving social/infrastructure systems toward sustainability; nor capturing infrastructure security as a critical component of sustainability in infrastructure systems. In addition, the existing systems do not seem to be differentiating between the higher-impact and lower-impact areas for moving transportation systems toward sustainability. Because this is a relatively rapidly growing area however, opportunities continue to exist for refining existing visions and indicator systems and advancing existing capabilities to support progress toward sustainable infrastructure systems.

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References

Ashley, R., and Hopkinson, P. (2002). "Sewer systems and performance indicators—Into the 21st century." *Urban Water*, 4(2), 123–135.

Balkema, A. J., Preisig, H. A., Otterpohl, R., and Lambert, F. J. D. (2002). "Indicators for the sustainability assessment of wastewater treatment systems." *Urban Water*, 4, 153–161.

Baltic 21. (2000). "Indicators on sustainable development in the Baltic Sea region (An initial Set)." *Baltic 21 Transport Sector Rep.—Indicators for Sustainable Transportation*, Stockholm, Sweden.

Bannister, D., and Pucher, J. (2003). "Can sustainability be made acceptable?" *Paper for Presentation at the Proc., 2nd STELLA focus group meeting on Institution, Regulation, and Markets in Transportation*. Sustainable Transport in Europe and Links and Liaisons with America (STELLA), Santa Barbara, Calif.

Black, J. A., Paez, A., and Suthanaya, P. A. (2002). "Sustainable urban transportation: Performance indicators and some analytical approaches." *J. Urban Plann. Dev.*, 128(4), 184–209.

Centre for Sustainable Transportation (CST). (2003). "Transportation performance indicators." CSR, Toronto, ⟨www.cstctd.org⟩, accessed September 2003.

Cortese, A. D. (2003). "The critical role of higher education in creating a sustainable future." *Planning Higher Education*, 31(3), 15–22.

Dawes, R. M. (1988). *Rational choice in an uncertain world*, Harcourt Brace College Publishers, San Diego.

Deakin, E. (2001–2003). "Sustainable development and sustainable transportation: Strategies for economic prosperity, environmental quality and equity." *Working Paper 2001-03*, Institute of Urban and Regional Development, Univ. of California at Berkeley, Berkeley, Calif.

Department of Sustainable Development (DSD). (2003). "Achieving a better quality of life, Review of progress towards sustainable development." United Kingdom ⟨http://www.sustainable-development.gov.uk/ar2002/pdf/ar2002.pdf⟩

Environment Canada. (1991). "A Report on Canada's Progress Towards a National Set of Environmental Indicators." *State of the Environment Rep. No. 91-1*, Minister of Supply and Services, Ottawa.

Environment Canada. (2003). "Environment signals: Canada's National Environmental Indicator Series." Canada.

Environmental Defense. (1999). "Environmental sustainability kit." Pollution Prevention Alliance, United States.

European Commission (Energy, Environment and Sustainable Development Programme, Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems (PROSPECTS). (2003). "Developing Sustainable Urban Land Use and Transport Strategies:" *Methodological guidebook*.

European Environment Agency (EEA). (2002). "Transport and environment reporting mechanism (TERM) 2002—Paving the way for EU enlargement: Indicators of transport and environment integration Environmental Issues." Copenhagen, Denmark.

Federico, C., Cloud, J. P., and Wheeler, K. (2003). "Kindergarten through twelfth grade education for sustainability." *Environmental law reporter*, Vol. 2, Environmental Law Institute, Washington, D.C.

Gilbert, R., and Tanguay, H. (2000). "Brief review of some relevant worldwide activity and development of an initial long list of indicators." Sustainable Transportation Performance Indicators (STPI) Project, Center for Sustainable Transportation (CST), Toronto.

Gudmundsson, H. (2000). "Indicators for performance measures for transportation, environment and sustainability in North America: Report from a German Marshall Fund Fellowship 2000 individual study tour October 2000." *Research Notes Rep. No. 148*, Ministry of Environment and Energy, National Environmental Research Institute, Denmark.

Litman, T. (2003). "Sustainable transportation indicators." Victoria Transport Policy Institute (VTPI), Victoria, Canada. ⟨http://www.vtpi.org/sus-indx.pdf⟩

Meyer, M. D., and Jacobs, L. J. (2000). "A Civil engineering curriculum for the future: The Georgia Tech Case." *J. Prof. Issues Eng. Educ. Pract.*, 126(2), 74–78.

National Round Table on the Environment and the Economy (NRTEE). (2003). "Environment and Sustainable Development Indicators for Canada, Ottawa, Ontario." ⟨http://www.nrtee-trnee.ca/eng/programs/Current_Programs/SDIndicators/ESDI-Report/ESDI-Report-E.pdf⟩, accessed October 2003.
New Zealand Ministry of the Environment (NZME). (1999). "Proposals for indicators of the environmental effects of transport." ⟨http://www.mfe.govt.nz/publications/ser/transport-proposals-full-jun99.pdf⟩
Ontario Round Table on Environment and Economy (ORTEE). (1995). "Sustainability indicators: The transportation sector." *Report*, ORTEE, Toronto.
Organization for Economic Cooperation and Development (OECD). (1999a). "Indicators for the integration of environmental concerns into transport policies." Environment Directorate, Paris.
Organization for Economic Cooperation and Development (OECD). (1999b). "Using the pressure-state-response model to develop indicators of sustainability." OECD Environmental Indicators.
Pearce, A. R. (2000). "Sustainability and the built environment: A metric and process for prioritizing improvement opportunities." PhD thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta.
Pearce, A. R., and Vanegas, J. A. (2002). "Defining sustainability for built environment systems." *Int. J. Environ. Technol. Manage.*, 2(1), 94–113.
Rijsberman, M. A., and van de Ven, F. H. M. (2000). "Different approaches to assessment of design and management of sustainable urban water systems." *Environ. Impact Assess. Rev.*, 20(3), 333–345.
Schwartz, P. (1996). *The art of the long view*, Doubleday, New York.
Segnestam, L. (1999). "Environmental performance indicators (second edition), Environmental Economics Series." *Paper No. 71*, The World Bank. ⟨http://wwwds.worldbank.org/servlet/WDSServlet?pcont=details&eid=000094946_00012505400754⟩
Transportation Association of Canada (TAC). (1999). "Urban transportation indicators." Ottawa. ⟨http://www.tac-atc.ca/english/productsandservices/ui/exec.asp⟩
Transport Canada (TC) (2001). "Sustainable development strategy 2001–2003, Ottawa: Transport Canada." ⟨http://www.tc.gc.ca/programs/environment/sd/strategy0103/actionplan.htm⟩
United States Department of Energy (USDOE). "Ten steps to sustainability." *Energy Efficiency and Renewable Energy Network* ⟨http://www.sustainable.doe.gov/management/tensteps.shtml⟩, accessed September 2003.
United States Department of Transportation (USDOT). (2003). *Performance Rep. No. 2004 Performance Plan*, Washington, D.C. ⟨http://www.dot.gov/PerfPlan2004/index.html⟩
United States Environmental Protection Agency (USEPA). (1999). *Indicators of the environmental impacts of transportation*, 2nd. Ed., Washington, D.C. ⟨http://www.epa.gov/otaq/transp/99indict.pdf⟩
Web Definitions (Indicators). (2001). ⟨www.scoea.bc.ca/glossary2001.htm⟩
Web Definitions (Metrics). ⟨www.summary.net/manual/glossary.html⟩
Wheeler, K. A., and Byrne, J. M. (2003). "K-12 sustainability education: Its status and where higher education intervenes." *Planning Higher Education*, 31(3), 23–29.
World Commission on Environment and Development (WCED). (1987). *Our common journey*, Oxford Univ. Press, Oxford, England.
Zegras, C., Sussman, J., and Christopher, C. (2004). "Scenario planning for strategic regional transportation planning." *J. Urban Plann. Dev.*, 130(1), 2–13.