

EVALUATING SUSTAINABILITY OF URBAN DEVELOPMENT IN DEVELOPING COUNTRIES INCORPORATING DYNAMIC CAUSE-EFFECT RELATIONSHIPS OVER TIME

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Abstract: There exist various factors influencing the sustainability of urban development. This paper attempts to establish a simplified dynamic structural equation model in order to capture complex cause-effect relationships existing in the measurement of sustainability over time, considering data availability in developing countries. Dynamic evaluation is realized by introducing the concept of state dependence and latent variables are introduced to represent indicators of urban sustainability, i.e., transportation, land use and energy consumption in this study. Then, an extensive set of land use, transportation and energy data, collected from 46 cities in developed and developing countries at three different points in time (1970, 80 and 90), is adopted. Model estimation results suggest the validity of the resultant model. Moreover, it is also confirmed that transport supply policies supporting economic activities were the main factors determining energy consumptions.

Key Words: sustainability of urban development, developing countries, dynamic structural equation model, indicator

1. INTRODUCTION

Developing countries are facing unprecedented challenges towards sustainable societies in the sense that they have to balance economic growth and environmental consideration even though they are not major contributors to environmental loads. There are numerous constraints that restrict societal development. Such constraints result from laws of nature, physical environment (e.g., available space, waste absorption capacity of soils, rivers, oceans, atmosphere, availability of renewable and non-renewable resources), solar energy flow and material resource stocks, carrying capacity, human actors, human organizations and cultures, technology, role of ethics and values, and available spectrum of diversity (Bossel, 1999). These constraints reduce the total range of future possibilities and consequently leave only a limited, potentially accessible set of options (i.e., accessibility space). Different from the situations at early development stage of developed countries, developing countries have to pay more and more attentions to such accessibility space in order to realize the same level of economic growth.

There exist different types of definitions of sustainable development. One of the most commonly cited definitions emphasizes the economic aspects by defining sustainable development as “economic development that meets the needs of the present generation

without compromising the ability of future generations to meet their own needs" (WCED, 1987), however, sustainable development of human society also has environmental, material, ecological, social, legal, cultural, political and psychological dimensions that require attentions (Bossel, 1999). Nowadays, global development regards sustainability as an explicit goal. But the concept has to be translated into the practical dimensions of the real world to make it operational. In this sense, it becomes more and more important how to realize sustainable development at urban level, where the increasing large percentage of human beings is residing in. These days, such importance of sustainability of urban development has been widely recognized by not only environmentalist, but also firms and governmental bodies (Newman, 1999).

There exist various factors influencing the sustainability of urban development, such as land use, travel behavior pattern and transportation networks, energy consumption pattern, and progress of technology, educational level and residents' environmental attitudes. These factors interact each other, and show temporally changing cause-effect relationships and impose varying influences on the sustainability at different stages of urban development. In this sense, sustainability is a dynamic concept. To evaluate the sustainability, it is therefore necessary to develop some comprehensive evaluation models by explicitly incorporating the interactions among these factors across space and over time. For example, integrated land use and transportation models (e.g., Timmermans, 2003) could play such role. However, such models with spatial interactions need spatial (zonal or mesh-type) data, which is usually not available and also difficult to be collected in developing countries. Accordingly, it is urged to develop some simplified evaluation models considering such data availability. Such simplified models could provide some practical indicators to policy makers. As pointed out by Segnestam (2002), indicators have been used for a long time as a tool with which more information can be obtained about issues as varied as people's health, weather, and economic welfare. Indicators provide information on matters of wider significance than what is actually measured or make perceptible a trend or phenomenon that is not immediately detectable (Hammond *et al*, 1995). Of course, indicators are not the end in themselves - they are the means to an end, consisting of improved decision-making. To get a step closer to that end, analyses based on indicators need to be carried out. These analyses result in information, which is the basis for sound decision-making (Segnestam, 2002).

Compared to indicators of economic and social aspects, environmental and sustainable development indicators are a relatively new phenomenon. The Rio Conference on Environment and Development in 1992, and other similar environmental milestone activities and happenings, recognized the need for better and more knowledge and information about environmental conditions, trends, and impacts. In recent years, a lot of work has been done on environmental and sustainable development indicators both at national and international level (Niemeijer, 2002). The geographic focus of these reports varies from regional (e.g., Jones *et al*, 1998) to national (e.g., The Heinz Center, 1999) to multi-national (e.g., World Economic Forum, 2001) and the focus ranges from a particular sector such as transport (e.g., EEA, 2000) or agriculture (e.g., MAFF, 2000) to the environment in its widest sense (e.g., EEA, 2001) by looking at indicators for sustainable development (e.g., IWG-SDI, 2001). Reports further vary in whether they look only at the state of the environment (e.g., NRC, 2000) or also at driving forces, pressures and responses (e.g., OECD, 2001).

Therefore, this paper attempts to develop a new dynamic evaluation model of urban development in order to provide some practical indicators for supporting policy decisions, considering the data availability in developing countries. The rest of paper is organized as follows. Section 3 discusses some methodological issues related to the development of dynamic evaluation models. Following that, section 4 introduces the data adopted in this study and describes the characteristics of some major factors related to the sustainable urban development. Section 5 estimates the dynamic model and discusses its performance in evaluating the sustainability of urban development. Finally, section 6 summarizes the study and mentions about some major challenges in the future.

2. EXISTING INDICATOR SYSTEMS OF SUSTAINABLE DEVELOPMENT

As argued by Bossel (1999), sustainable development has become a widely recognized goal for human society ever since deteriorating environmental conditions in many parts of the world indicate that its sustainability may be at stake. To understand current situations, one needs appropriate indicators. Finding an appropriate set of indicators of sustainable development for a community, a city, a region, a country or even the world is not an easy task. Here, it is attempted to briefly review main indicator systems of sustainable development, including 1) The Genuine Progress Indicator (Redefining Progress, 1999), 2) Millennium Development Goals (UNPD, 2003), 3) Indicators of Sustainable Development by UNCSD (2000), 4) *Dashboard* by IISD (2002), 5) Indicators of Sustainable Community (AtKisson *et al.*, 1997 and AtKisson, 2004), 6) Environmental Sustainability Index (World Economic Forum, 2001), and 7) Environmental Indicators by European Environmental Agency (EEA, 1999).

2.1 The Genuine Progress Indicator

As argued by Redefining Progress (1999), GDP is badly flawed as a measure of economic health because it counts only monetary transactions as economic activity, and ignores much of what people value and activities that serve basic needs, the value of leisure time spent in recreation, relaxation, or with family and friends, crucial contributions of the environment, such as pure air and water, and environmental costs of economic activities and so on. To address the inadequacies of the GDP as a new measure of the economic wellbeing of the nation, the Genuine Progress Indicator (GPI) was developed in 1994 by *Redefining Progress*, a nonprofit, nonpartisan public policy institute. It has been measured for each nation from 1950 to the present. The contents of GPI include crime and family breakdown, household and volunteer work, income distribution, resource depletion, pollution, long-term environmental damage, changes in leisure time, defensive expenditures, lifespan of consumer durables and public infrastructure, and dependence on foreign assets.

2.2 Millennium Development Goals

According to Segnestam (2002), the Development Assistance Committee of the Organization for Economic Co-operation and Development initiated the development of the indicators for the called International Development Goals (IDGs) initiative, inviting the United Nations, the World Bank and the International Monetary Fund to become partners, in 1996. Over the four years that followed, five working groups discussed indicators for issues such as poverty, education, gender, infant and child mortality, maternal health, HIV/AIDS, malaria and other diseases, environment, and global partnership. At a later stage, the name of the targets changed from the IDGs to the MDGs (the Millennium Development Goals). Each goal has a number of targets identified. In total, eight goals and eighteen targets were finally proposed. In 2000, the UN Millennium Declaration, adopted at the largest-ever gathering of heads of state, committed countries - rich and poor - to doing all they can to eradicate poverty, promote human dignity and equality and achieve peace, democracy and environmental sustainability (UNPD, 2003).

2.3 Indicators for Sustainable Development

Indicators for monitoring progress towards sustainable development are needed in order to assist decision-makers and policy-makers at all levels and to increase focus on sustainable development. Beyond the commonly used economic indicators of well-being, however, social, environmental and institutional indicators have to be taken into account as well to arrive at a broader, more complete picture of societal development. At its Third Session in 1995, the Commission on Sustainable Development (CSD) of United Nations initiated the development of indicators for the measurement of sustainable development. Major areas cover social, environmental, economic and institutional aspects. A working list of 134 indicators was selected and 22 countries volunteered to test their applicability, by using a framework based on environmental (sustainable development) themes (UNCSD, 2000).

2.4 *Dashboard*

Dashboard was proposed by the International Institute of Sustainable Development (IISD).

Dashboard consists of four categories of society, environment, economy and institutions and category index is calculated from individual indicators in each (IISD, 2002). Social category includes 18 indicators, e.g., poverty, equity, unemployment, child weight, child mortality, life expectancy, safe water, crowding, population growth and urbanization etc. Environmental category has 19 indicators including CO₂, crop land, forest area, key ecosystem, mammals and birds, and protected area and so on. Economic category includes 13 indicators such as GNP, ODA, energy use and efficiency, waste and recycling, and car use. Finally, institutional category has 8 indicators, which are SD strategy, SD membership, Internet, telephones, R&D expenditure, disasters (human cost and economic damage) and SD indicator coverage. Institutional aspects could be used to measure the capacity of government.

2.5 Indicators of Sustainable Community: Sustainable Seattle Indicators

A famous and often copied example is the set of indicators of sustainable development for the city of Seattle, Washington. This set is the result of a long process of discussion and development, involving intensive citizen participation (AtKisson *et al*, 1997; AtKisson, 2004). When Sustainable Seattle participants first began meeting in the early Spring of 1991, sustainability was a new concept to most people in public life. For many nations, the Brundtland Commission report became a call to action. But the U.S. government had expressed little interest in the concept, leaving most members of the public uninformed. However, Seattle's Mayor and the President of its City Council both made strongly supportive statements about the project to the press. After 5 years of steady work by legions of volunteers, *Sustainable Seattle* had overcome numerous barriers, including the need to (1) build trust among diverse participants, (2) establish credibility and legitimacy in the eyes of decision makers and the media, (3) mobilize and retain highly skilled volunteers, (4) include the creative participation of hundreds of citizens, and (5) meet the technical challenge of finding and presenting data for 40 long-term trends. But since its inception, production of the indicators report--now projected to be updated every 2 to 3 years (AtKisson, 2004). Sustainable Seattle Indicators cover environment, population and resources, economy, youth and education, health and community.

2.6 Environmental Sustainability Index

The Environmental Sustainability Index (ESI) sponsored by the World Economic Forum is designed to provide national level figures on environmental sustainability for, at present, 122 nations across the globe (World Economic Forum, 2001). The ESI is an initiative of the Global Leaders of Tomorrow Environment Task Force of the World Economic Forum in collaboration with the Yale Center for Environmental Law and Policy (YCELP) of Yale University and the Center for International Earth Science Information Network (CIESIN) of Columbia University. The ESI consists of five dimensions or components: environmental systems, reducing environmental stresses, reducing human vulnerability, social and institutional capacity and global stewardship. The ESI is developed partly based on the pressure-state-response (PSR) or driving force-state response (DSR) frameworks, which have their origin in work by the OECD, Canadian government and UNEP (Hammond *et al*, 1995; OECD, 1999). Pressure on the environment from human and economic activities, lead to changes in the state or environmental conditions that prevail as a result of that pressure and may provoke responses by society to change the pressures and state of the environment (OECD, 1999). In this light the environmental stresses component of the ESI corresponds with the pressure component of the PSR framework. The environmental systems component of the ESI corresponds with the state component of the PSR framework and to some degree the same can be said about the human vulnerability component of the ESI, which reflects the state of the human system. Finally, the social and institutional capacity and global stewardship reflects different aspects of the response component of the PSR framework. Whereby, it should be remarked that the global stewardship component also contains some typical pressure variables in its protecting international commons indicator (Niemeijer, 2002).

2.7 Environmental Indicators by European Environmental Agency

European Environmental Agency (EEA) has developed various indicators related to agriculture, air, biodiversity change, climate change, coasts and seas, energy, fisheries, households, nature, soil, tourism, transport, and water, based on the DPSIR framework

proposed by OECD (VRDC, 2001), which will be described later. EEA (1999) argues that indicators can be classified into four simple groups, which address the following questions:

- What is happening to the environment and to humans? (Descriptive Indicators)
- Does it matter? (Performance indicators)
- Are we improving? (Efficiency indicators)
- Are we on the whole better off? (Total Welfare indicators)

Descriptive indicators describe the actual situation with regard to the main environmental issues, such as climate change, acidification, toxic contamination and wastes in relation to the geographical levels at which these issues manifest themselves. Performance indicators compare actual conditions with a specific set of reference conditions. They measure the distance between current environmental situation and the desired situation (target). Most countries and international bodies currently develop performance indicators for monitoring their progress towards environmental targets. On the other hand, efficiency indicators provide insight in the efficiency of products and processes, in terms of the resources used, the emissions and waste generated per unit of desired output. The most commonly used efficiency indicators express the amount of emissions or energy used per capita or per unit of GDP. Total welfare indicators are used to measure total sustainability, such as the Index of Sustainable Economic Welfare (ISEW).

From the above-mentioned review, it is obvious that most of the existing indicator systems have been developed at nation-level, and relevant indicators at city level are very limited. This becomes a barrier of translating the concept of sustainability into the practical dimensions of real world. Furthermore, interdependencies among different indicators have not explicitly represented, even though they have been conceptually discussed. Therefore, this study focuses on the development of sustainability indicators at city level, explicitly and systematically incorporating the interdependencies among indicators.

3. METHODOLOGY OF DEVELOPING SUSTAINABILITY INDICATORS

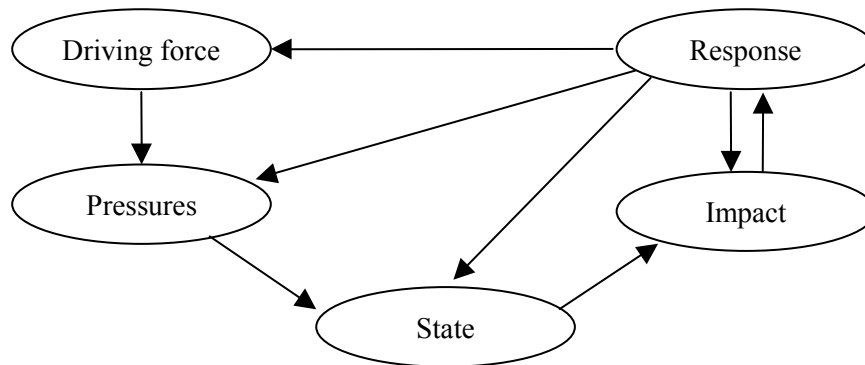
It is well known that developing any types of models will definitely receive more or less constrains from the available data. This is also true for the development of sustainability indicators. Work on the development of indicators ranges from exploiting existing data to best characterize the state of the environment to determining the theoretically best possible indicators as points of departure for future data collection and stock-taking (Niemeijer, 2002). The former is called data-driven approach, which argues that data availability is the central criterion for indicator development and data is provided for all selected indicators. The latter is called theory-driven approach, which focuses on selecting the best possible indicators from a theoretical point of view, while data availability is only considered one of the many aspects to take into account. Here, two representative methodologies related to the indicator development in this study are first summarized. One is a data-driven approach, called DPSIR framework (OECD, 1999; VRDC, 2001), and another is a theory-driven approach, called system approach (Bossel, 1999).

3.1 Data-Driven Approach: DPSIR Framework

DPSIR framework (see Figure 1) was proposed by OECD (1999) and is widely applied to sustainable development problems at nation level. In the framework, social and economic developments exert *pressure* (*P*) on the environment and, as a result, the *state* (*S*) of the environment changes, such as the provision of adequate conditions for health, resources availability and biodiversity. This leads to *impacts* (*I*) on human health, ecosystems and materials that may elicit a societal *response* (*R*) that feed back on the *driving* forces (*D*), or on the *state* or *impacts* directly.

Concretely speaking, indicators for *driving forces* describe social, demographic and economic developments in societies and the corresponding changes in life styles, overall levels of consumption and production patterns. Primary *driving forces* are population growth and developments in the needs and activities of individuals. *Pressure* indicators describe

developments in release of substances (emissions), physical and biological agents, the use of resources and the use of land. Examples of *pressure* indicators are CO₂-emissions per sector, the use of rock, gravel and sand for construction and the amount of land used for roads. *State* indicators give a description of the quantity and quality of physical phenomena (such as temperature), biological phenomena (such as fish stocks) and chemical phenomena (such as atmospheric CO₂- concentrations) in a certain area. Due to *pressure* on the environment, the *state* of the environment changes. These changes then have *impacts* on the social and economic functions on the environment, such as the provision of adequate conditions for health, resources availability and biodiversity. *Response* indicators refer to responses by groups (and individuals) in society, as well as government attempts to prevent, compensate, ameliorate or adapt to changes in the state of the environment (VRDC, 2001).



Source: OECD (1999) and VRDC (2001)

Figure 1. DPSIR framework developed by OECD

3.2 Theory-Driven Approach: System Approach

Sustainable urban development involves complex decision-making process. To properly identify the vital aspects of such decisions, system approach is preferred. As described by Bossel (1999), a system is anything that is composed of system elements connected in a characteristic system structure. This configuration of system elements allows it to perform specific system functions in its system environment. Bossel (1999) proposed to apply orientation theory, which was developed in the 1970s in an effort to understand and analyze the diverging visions of the future and normative interests of different societal actors (political parties, industry, environmental NGOs), and to define criteria and indicators for sustainable development (Bossel, 1987). Six fundamental properties are relevant, i.e., normal environmental state, resource scarcity, variety, variability, change and other systems. These environmental properties can be viewed as imposing certain requirements and restrictions on systems, which orient their functions, development and behavior. Basic orientors consist of environment-determined orientors and system-determined orientors. The former includes existence, effectiveness, and freedom of action, security, adaptability, and coexistence. The latter includes reproduction, psychological needs and responsibility (Bossel, 1999). These basic orientors are unique in the sense that one orientor cannot substitute for another. Bossel (1999) argues that orientation theory could be used to develop a general method for finding a comprehensive set of indicators of sustainable development.

Even though theory-driven approach is desirable, this study suggests applying the data-driven approach in this study, considering the limitation of available data in developing countries. However, the most serious disadvantage of DPSIR is that it neglects the systemic and dynamic nature of the processes, and their embedding in a larger total system containing many feedback loops. To make full use of the advantages of data-driven approach and overcome its shortcomings, structural equation model seems promising.

3.3 Structural Equation Models

Considering the data availability in developing countries, in order to capture the complex cause-effect relationships existing in the measurement of sustainability, this study proposes to apply a structural equation model, which is a set of simultaneous equations. Structural

equation models have been proven useful in solving many substantive research problems in social and behavioral sciences. Such models have been used in the study of macroeconomic policy formation, intergenerational occupational mobility, racial discrimination in employment, housing and earnings, studies of antecedents and consequences of drug use, scholastic achievement, evaluation of social action programs, voting behavior, studies of genetic and cultural effects, factors in cognitive test performance, consumer behavior, and many other phenomena including transportation. Methodologically, the models play many roles, including simultaneous equation systems, linear causal analysis, path analysis, structural equation models, dependence analysis, and cross-legged panel correlation technique (Jöreskog and Sörbom, 1989). Structural equation model is used to specify the phenomenon under study in terms of putative cause-effect variables and their indicators. Following the descriptions by Jöreskog and Sörbom (1989), the full model structure can be summarized by the following three equations.

Structural Equation Model:

$$\eta = B\eta + \Gamma\xi + \zeta \quad (1)$$

Measurement Model for y :

$$y = \Lambda_y\eta + \varepsilon \quad (2)$$

Measurement Model for x :

$$x = \Lambda_x\xi + \delta \quad (3)$$

Here, $\eta' = (\eta_1, \eta_2, \dots, \eta_m)$ and $\xi' = (\xi_1, \xi_2, \dots, \xi_m)$ are latent dependent and independent variables, respectively. Vectors η and ξ are not observed, but instead $y' = (y_1, y_2, \dots, y_p)$ and $x' = (x_1, x_2, \dots, x_q)$ are observed dependent and independent variables. $\zeta, \varepsilon, \delta$ are the vectors of error terms, and $B, \Gamma, \Lambda_x, \Lambda_y$ are the unknown parameters.

As mentioned at section 1, sustainability has various dimensions including economic, environmental, material, ecological, social, legal, cultural, political and psychological dimensions. It is desirable to comprehensively represent the cause-effect relationships existing in the concept of sustainability based on the theory-driven approach such as system approach. However, it is still difficult to apply the theory-driven approach because of data availability. In this sense, it is realistic to adopt the data-driven approach. This study proposes a dynamic structural equation model (see Figure 2), where *land use*, *transport supply* and *demand*, and *environmental loads*, defined as latent variables, are introduced to represent urban sustainability. The model structure itself is similar to the DPSIR framework. The difference is that the new model endogenously represents the cause-effect relationships among the four elements related to urban sustainability. In addition, the dynamic cause-effect relationships are also incorporated in the model based on the concept of state dependence, which indicates the influence of a dependent variable at time $t-1$ on the one at time t .

4. DATA AND FINDINGS

This paper uses the data from 46 cities in developed and developing countries, collected by Kenworthy *et al* (2000). The data contain an extensive set of land use, transportation and energy data on 46 cities in the world at four different points in time (1960, 70, 80 and 90). The cities are shown in Table 1. The characteristics of main factors in the data are respectively shown in Figure 3 (population), Figure 4 (vehicle ownership), Figure 5 (length of road), Figure 6 (parking spaces at CBD), Figures 7 and 8 (travel distance by car and public transport systems), Figures 9 and 10 (energy use by car and public transport systems) and Figures 11 and 12 (relationships between gross regional product (GRP) and environmental emission). The data shown in these figures suggest that considering current limited transportation supply, environmental issues in developing countries will be further worsened due to rapid population growth and vehicle ownership.

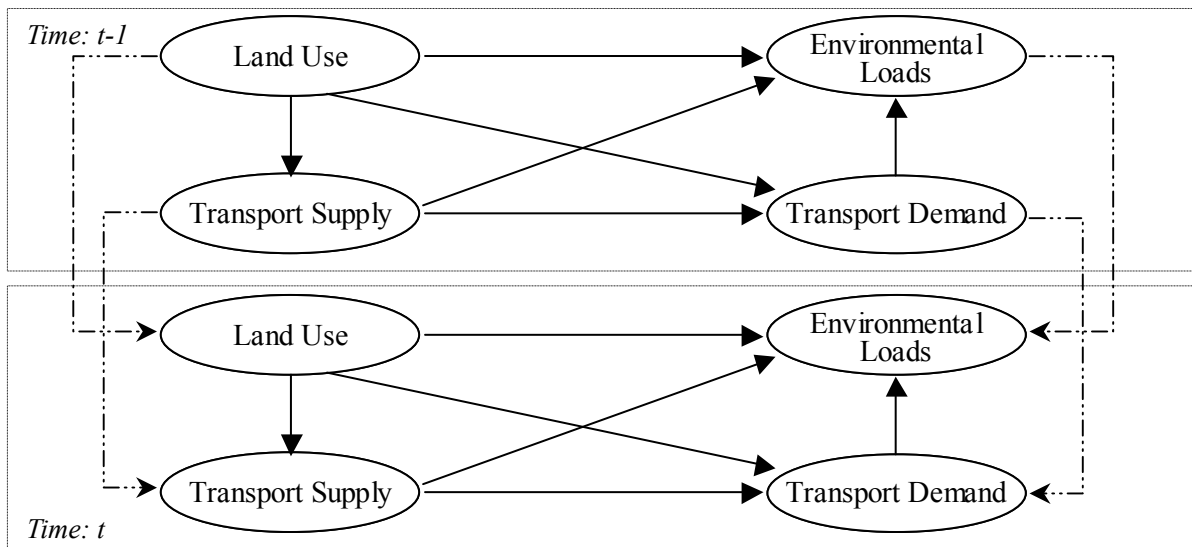


Figure 2. Conceptual dynamic model structure of DPSIR framework

Table 1. Target cities used in the analysis

US cities	Australia cities	Canadian cities	European cities	Wealthy Asian cities	Developing Asian cities
Boston	Adelaide	Calgary	Amsterdam	Hong Kong	Bangkok
Chicago	Brisbane	Edmonton	Brussels	Singapore	Jakarta
Detroit	Canberra	Montreal	Copenhagen	Tokyo	Kuala Lumpur
Denver	Melbourne	Ottawa	Frankfurt		Manila
Houston	Perth	Toronto	Hamburg		Seoul
Los Angeles	Sydney	Vancouver	Landon		Surabaya
New York		Winnipeg	Munich		
Phoenix			Paris		
Portland			Stockholm		
Sacramento			Vienna		
San Diego			Zurich		
San Francisco					
Washington					

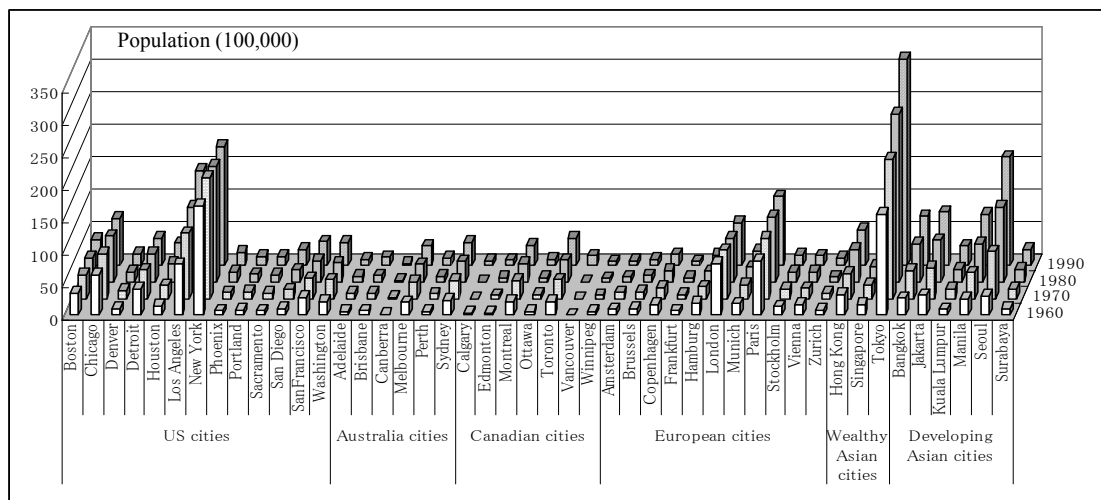


Figure 3. Population growths in developed and developing cities

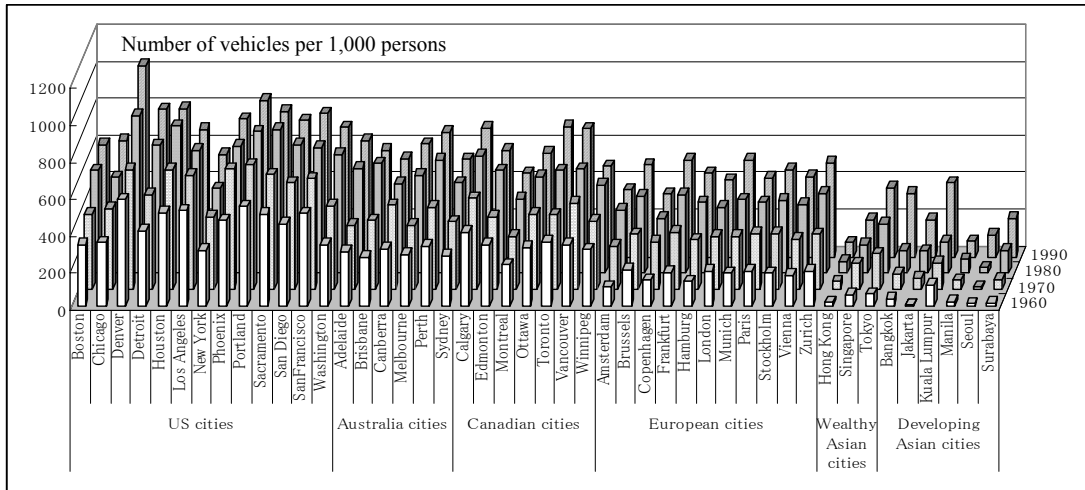


Figure 4. Vehicle ownership in developed and developing cities

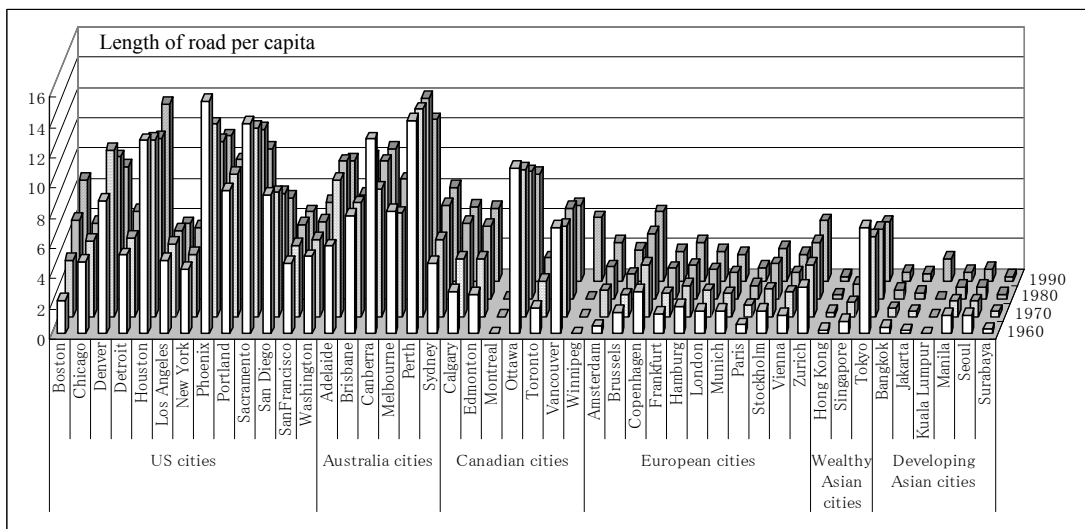


Figure 5. Length of road in developed and developing cities

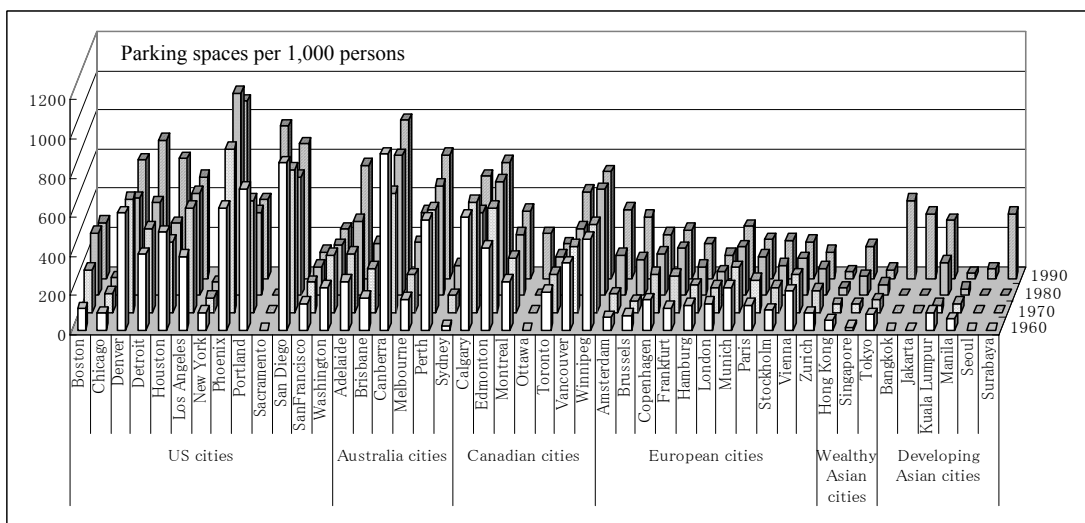


Figure 6. Parking spaces at CBD in developed and developing cities

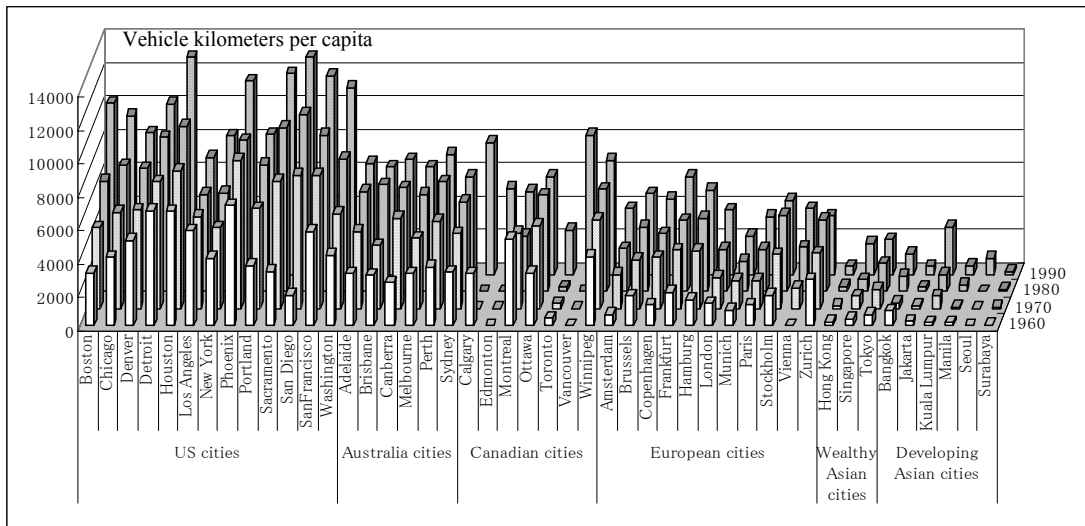


Figure 7. Travel distance by passenger cars in developed and developing cities

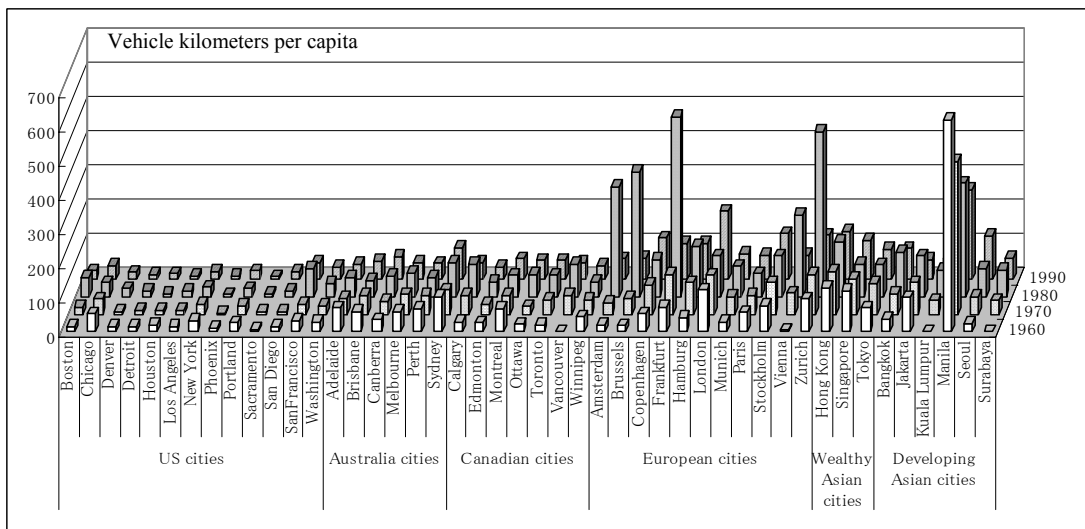


Figure 8. Travel distance by public transport systems in developed and developing cities

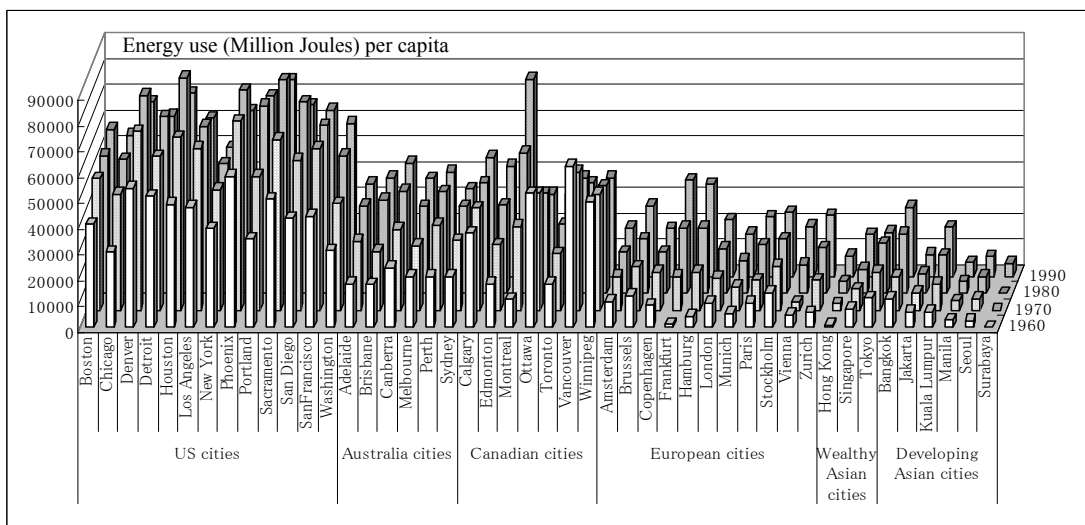


Figure 9. Energy use by passenger cars in developed and developing cities

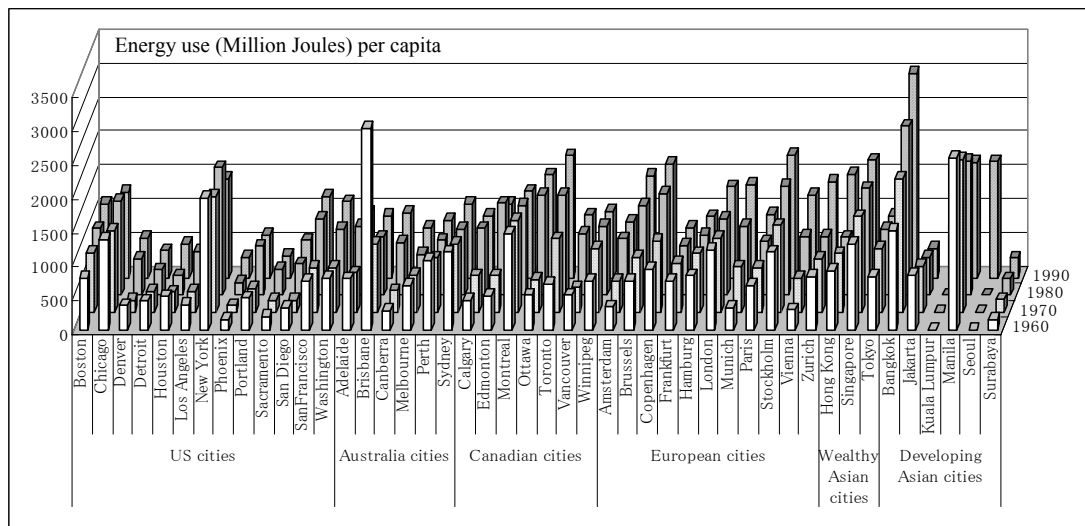


Figure 10. Energy use by public transport systems in developed and developing cities

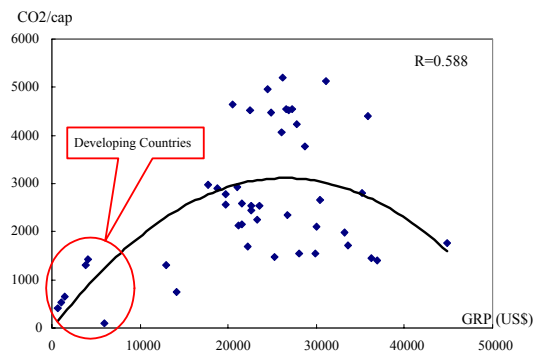


Figure 11. GRP and CO₂ in 1990

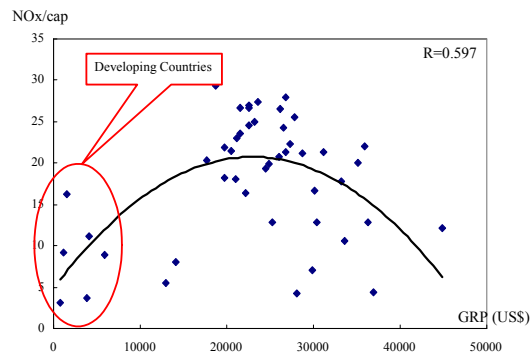


Figure 12. GRP and NO_x in 1990

Figures 11 and 12 also support the well-established convex relationship between economic activities and environmental emission (i.e. Environmental Kuznets Curve). This also indicates an important finding that, as the economic conditions in developing countries will be improved in the future, the environmental emissions from transport sector will keep increasing. However, when the economic development reaches certain level, it also has some possibilities to reduce the environmental emissions as long as the developing cities can learn positive aspects in transportation policies implemented by the developed cities.

5. ESTIMATION AND DISCUSSION OF DYNAMIC EVALUATION MODEL

Even though the data collected by Kenworthy *et al* (2000) contain an extensive set of land use, transportation and energy data, it is still difficult to provide sufficient information needed by the DPSIR framework, which is developed in the context of evaluating the sustainability at nation level. The reason why the data is adopted in this study is because it also includes the information at different points in time, which can be used to describe the dynamic cause-effect relationships among land use, transportation and energy. Even though sustainability has economic, environmental, material, ecological, social, legal, cultural, political and psychological dimensions, as mentioned at section 1, this paper attempts to evaluate urban sustainability based on *land use, transportation and energy consumption* (alternative variable of environmental loads), considering data availability. *Transportation* is further divided into *transport demand* and *transport supply*, because these two new latent variables represent two completely different aspects of transportation system.

Since there exist a relatively large amount of missing data in 1960, before clarifying the

suitable imputation method for the missing data in this study, as an initial attempt, this study only uses the data from the other three points in time (i.e., 1970, 1980 and 1990) for the model estimation. Structural equation model is first applied to describe the pooled data in 1970, 1980 and 1990. Based on a *trial and error* preliminary analysis, the latent variable “land use” is represented by using the population proportion at CBD (%Pop at CBD), population proportion at inner area (%Pop at Inner Area), job proportion at CBD (%Job at CBD), and job proportion at inner area (%Job at Inner Area). *Transport supply* is defined based on the parking spaces per 1000 persons at CBD (Parking Spaces/1000 at CBD), length of road per capita and vehicle ownership per 1000 persons (Vehicle Ownership/1000). VKT (vehicle kilometers traveled) ratios between car and other travel modes (bus, rail and other public transport (PT) system) are used to describe the latent variable *transport demand*: %VKT_Bus/Car, %VKT_Rail/Car and %VKT_Other PT/Car. Finally, the observed variables for *energy consumption* include energy consumption ratios between car and other travel modes: %EC_Bus/Car, %EC_Rail/Car and %EC_Other PT/Car.

The model is estimated by applying the software AMOS 4.0 (Arbuckle and Wothke, 1999) and its estimation results are shown in Figure 13. Standardized results are shown to directly compare the influences of different factors with different scales. They are calculated based on the original estimated parameters and their standard deviations obtained from the non-standardized results. The calculated GFI (0.700) and AGFI (0.600) suggest that the resultant model has a satisfactory goodness-of-fit index. Most of the estimated parameters are statistically significant. Moreover, the signs of the parameters empirically support the assumptions mentioned at the previous paragraph. Findings from Figure 13 can be summarized as follows:

- 1) Intensive *land use* at CBD and inner city area results in the decrease of parking spaces, length of road and vehicle ownership. This consequently leads to the reduction in private transport demand and increase in the use of public transportation systems. From the total effects on *transport demand*, it is obvious that *land use* has larger influence on *transport demand* than *transport supply*, because the total effect of *land use* is 0.54 and the one of *transport supply* is -0.38.
- 2) Increasing population and jobs at CBD is the best way to reduce the vehicle ownership.
- 3) Bus energy efficiency negatively affects energy consumption, suggesting that progress of technology could result in the reduction in *energy consumption*.
- 4) Concerning *energy consumption*, the highest total effect is observed with respect to *land use* ($0.45=0.14+0.27*0.35+0.72*0.16+0.72*0.38*0.35$). *Transport demand* is ranked in the second place (0.35) and *transport supply* in the last place ($-0.293=-0.16-0.38*0.35$). Since the observed variables (i.e., proportion of population and jobs at CBD and inner area) can be also used to partially represent the land use pattern, intensive land use can contribute to the remarkable reduction of energy use in private transportation systems and consequently reduce environmental emissions.

Based on the above cross-sectional estimation results from the pooled model, it can be concluded that increasing urban density at central areas could largely improve the level of sustainability, comparing with the control policy about transportation systems. This finding from cross-sectional analysis supports the widely accepted urban planning concept, i.e., compact city.

To confirm if such observation will be consistent over time and further capture the dynamic characteristics of urban sustainability, a dynamic model with the structure shown in Figure 2 is established. It is assumed that cause-effect parameters related to *land use*, *transport supply*, *transport demand* and *energy consumption* are invariant over time. Instead, to represent the temporal change in the level of sustainability, state dependence parameter is introduced with respect to each latent variable. Such assumption is made considering the limited sample size used in this study.

Each latent variable is first calculated from the above-mentioned pooled model (Figure 13). Then, based on these calculated latent variables, the dynamic model is estimated and its estimation results are shown in Figure 14. Here, it is further assumed that parameter of state

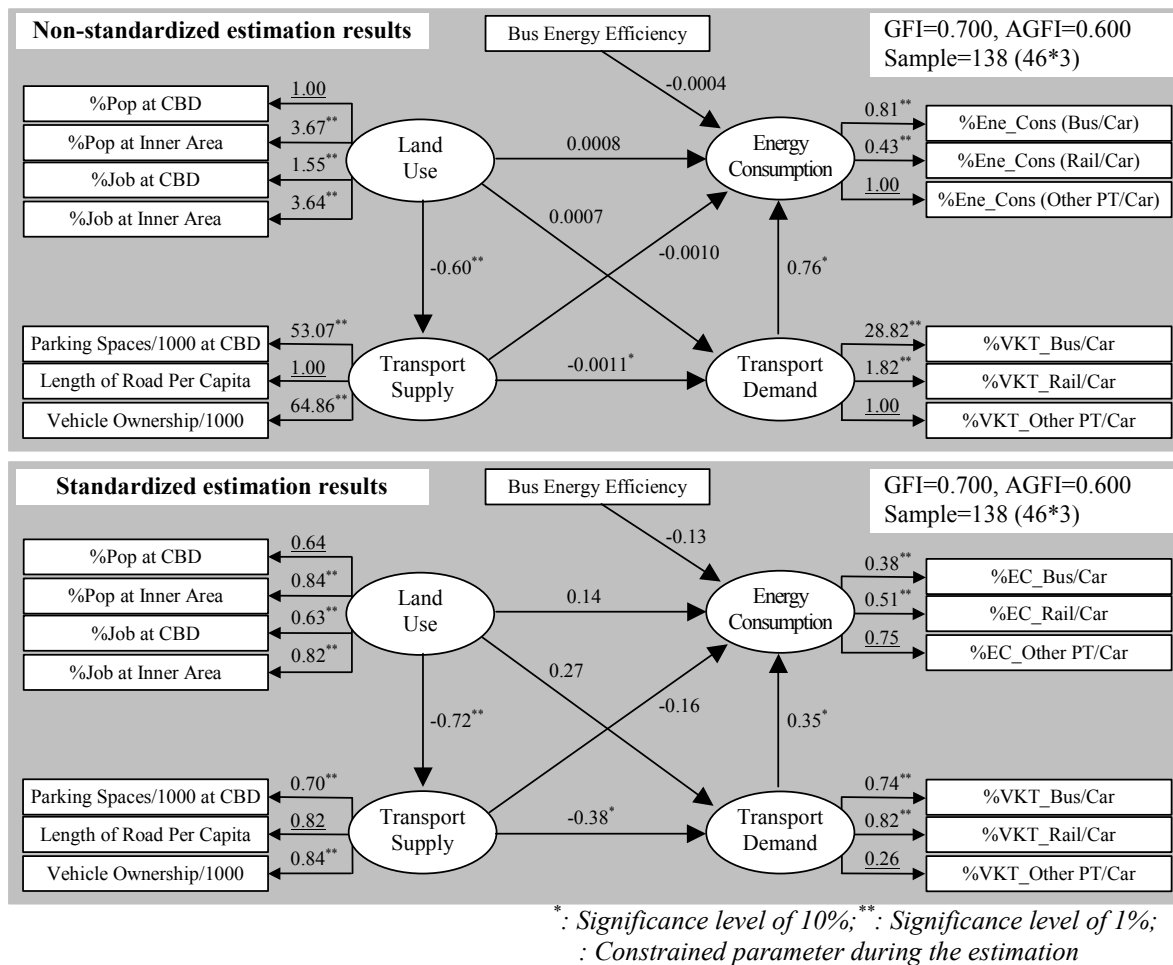
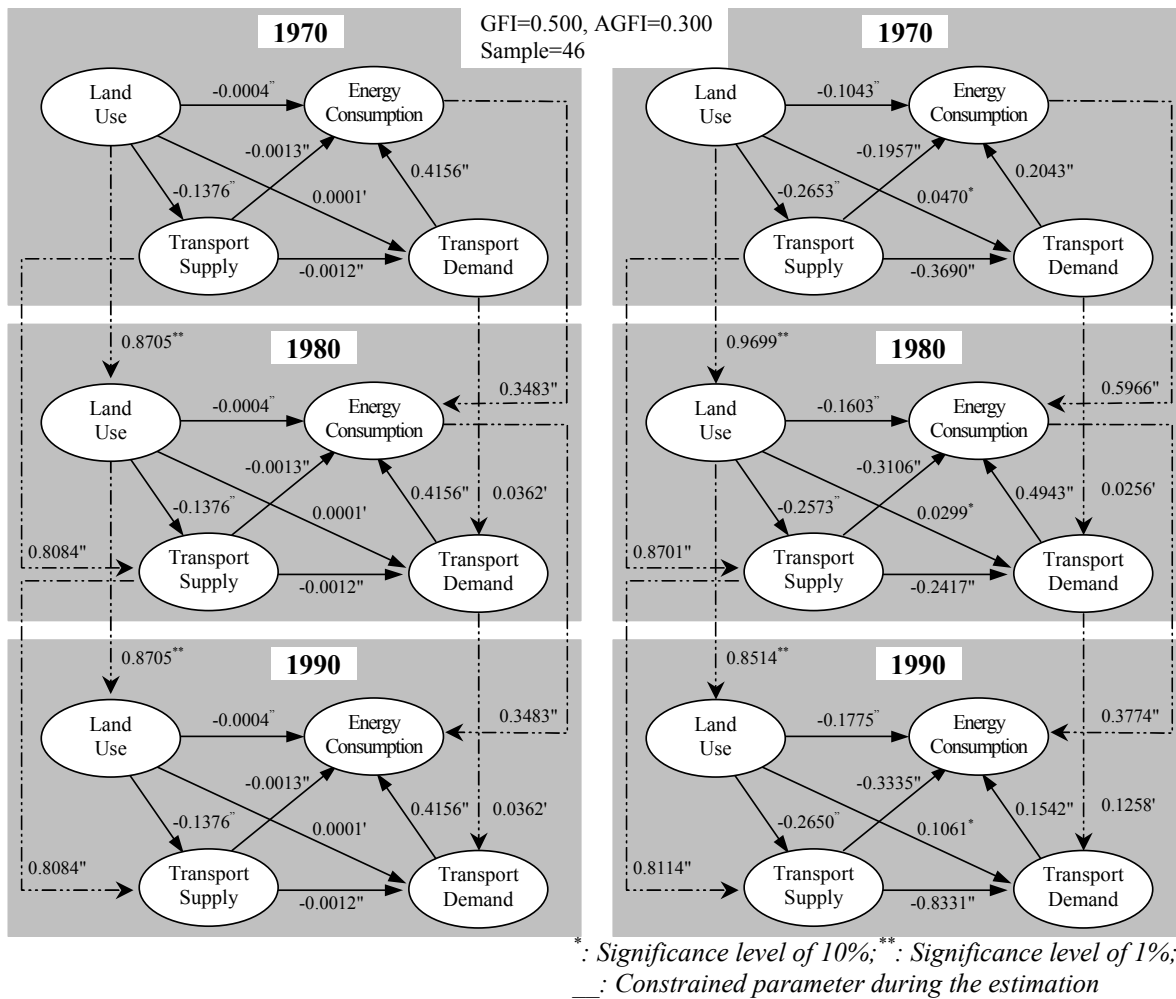


Figure 13. Standardized and non-standardized estimation results of the pooled model

dependence does not change over time. Such assumption makes the future prediction possible. This is a convenient way to evaluate the urban policies, especially in developing countries.

One can observe that all the parameters of state dependence are statistically significant and have positive signs. This supports the rationality of introducing state dependence. All of the other parameters are also significant and have expected signs. These results suggest the validity of the proposed model structure. However, model accuracy is not high enough. This might be caused by several reasons. Limitation of sample size (46 cities in this study) can be regarded as the top reason. Considering that it is usually difficult to collect the relevant data, especially time series data, at city level, more efficient estimation methods should be developed with respect to the case of small sample size. At the same time, carefully transforming some explanatory variables might be helpful. Since the main purpose of this study is to confirm the effectiveness of applying structural equation model to evaluate the urban sustainability, the above-mentioned issues are left as future research issues.

To evaluate the dynamic characteristics of urban sustainability, the total effects from the dynamic model (Figure 14) are calculated and shown in Table 2. The temporally changing total effects result due to the accumulating effects of state dependence parameter, even though it is assumed invariant over time. Focusing on *energy consumption* in 1980, it receives the largest influence from *energy consumption* in 1970. *Transport supply* in 1970 is ranked at the second place. This implies that *energy consumption* in 1980 is mainly determined by the habit of energy consumption behavior and transport supply policies in previous time. On the other hand, the top three factors affecting *energy consumption* in 1990 are all from *transport supply*, especially from the one in the past. This means that transport supply policies supporting economic activities in the past largely determined the energy consumption patterns in 1990. Contrary to the observation in the cross-sectional model, the influence of *land use* on



(a) Non-standardized estimation results (b) Standardized estimation results
Figure 14. Standardized and non-standardized estimation results of the dynamic model

energy consumption is very limited in the dynamic context. This study also estimated other types of model structures by relaxing the above-mentioned assumptions, however, the conclusions about “land use” were the same. As discussed in section 2, the existing indicator frameworks of sustainable development have been ignoring the quantitative cause-effect relationships among indicators. In contrast, the proposed dynamic model based on the data collected at city level can produce the relevant sustainability indicators explicitly incorporating the endogenous cause-effect relationships. Joint use of the data from the developed cities could provide some good benchmarks for improving the sustainability level in the developing cities.

6. CONCLUSIONS AND FUTURE RESEARCH ISSUES

Sustainability has various dimensions and is affected by various factors. These dimensions and/or factors may not be the same at different stages of urban development. To capture the dynamic characteristics of sustainability comprehensively, theory-driven approaches such as system approach are preferred. Such approaches usually need a large set of data, which is possibly collected in developed countries, however, is very difficult to be done in developing countries. To support policy decisions in developing countries that are facing unprecedented challenges towards sustainable societies, some practical, cost-effective and easily measured indicators are needed. This study therefore focuses on developing such indicators at city level based on a data-driven approach, considering the data availability in developing countries. As a result, a dynamic structural equation model is established, where dynamics are captured based on the concept of state dependence and latent variable is used to derive the indicators of

urban sustainability. It is confirmed that 1) the structural equation model and data source provided by Kenworthy *et al* (2000) can be used to derive the relevant sustainability indicators of urban development in the context of developing countries. Especially, the proposed model explicitly takes into account the cause-effect relationships among the indicators over time. Such dynamic cause-effect relationships have been ignored in the existing indicator frameworks. As for the policy aspects, it is found that transport supply policies supporting economic activities were the main factors determining the energy consumptions and land use policies only played a very limited role.

Table 2. Standardized total effects from dynamic model

Total Effect	Land Use in 1970	Land Use in 1980	Land Use in 1990	Travel Supply in 1970	Travel Supply in 1980	Travel Supply in 1990	Travel Demand in 1970	Travel Demand in 1980	Travel Demand in 1990	Energy Consumption in 1970	Energy Consumption in 1980
Energy Consumption in 1970	-0.0228			-0.2711			0.2043				
Energy Consumption in 1980	0.0535	-0.0350		-0.5403	-0.4297		0.1346	0.4943		0.5966	
Energy Consumption in 1990	0.1712	0.0520	-0.0387	-0.5343	-0.5417	-0.4620	0.0513	0.2059	0.1542	0.2251	0.3773
Travel Demand in 1970	0.1449			-0.3690							
Travel Demand in 1980	0.1488	0.0921		-0.2198	-0.2417		0.0256				
Travel Demand in 1990	0.6133	0.4637	0.3268	-0.6158	-0.7064	-0.8331	0.0032	0.1258			
Travel Supply in 1970	-0.2653										
Travel Supply in 1980	-0.4804	-0.2573		0.8700							
Travel Supply in 1990	-0.6086	-0.4343	-0.2650	0.7060	0.8114						
Land Use in 1980	0.9699										
Land Use in 1990	0.8258	0.8514									

As for future research issues, the above conclusions should be further examined based on some more efficient estimation methods suitable to the case of small sample size. In addition, this study estimated the pooled model and dynamic model independently. These two models should be repeatedly estimated to obtain the consistent values of parameters. The convex relationship between economic activities and environmental emission observed in Figures 11 and 12 also needs to be reflected in the linear model structure by, for example, properly transforming the relevant variables. This paper confirmed the effectiveness of the dynamic model to overcome methodological shortcomings in existing indicator frameworks based on internal validity (goodness-of-fit). It is necessary to examine external validity, i.e., temporal and spatial transferability. It is also an interesting research topic how to represent the missing data as well as serial correlation and heterogeneity. Furthermore, evaluation of urban sustainability should not ignore social dimensions (e.g., equity). Finally, it seems worthwhile to evaluate the effects of policies contributing to the sustainable urban development in developing cities.

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