A COMPARATIVE APPROACH OF THE QUANTITATIVE MODELS FOR SUSTAINABLE TRANSPORTATION

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Abstract: Based on the theories of sustainable development, this paper firstly presents a conceptual framework of sustainable transportation including definition, goals, objectives and assessment methods. Secondly, several quantitative models to measure transportation sustainability are reviewed and summarized. Finally, comparing with system dynamics models and optimization models only assessment indicator models are chosen and used to assess and valuate transportation sustainability by taking Taiwan as the case study considering data requirements and availability.

Key Words: Sustainable Transportation, Sustainability, Assessment Indicator Models, System Dynamics Models, Optimization Models

1. INTRODUCTION

The history of transportation systems is one of technical revolutions caused by the needs of greater mobility. New transportation technologies have been vital to the growth of mobility patterns since the onset of the Industrial Revolution. Linking with economic history, the transportation revolutions even create periods of economic development, e.g. the “age of canals” in the first half of the 19^{th} century and the “railway and coal era” during the booming period that ended with the Great Depression in the 1930s. Automobile manufactures become the symbol of the present period and are one of the main contributing factors to the unprecedented period of expansion in the economic history of mankind.

However, the growth in the number of automobiles causes environmental as well as other burdens to citizens and nature. Motorized vehicles contribute about 20 to 25% of worldwide CO_2 emissions, most of which are produced by the highly industrialized countries. Without the industrialized countries (especially the US) reducing energy consumption there is no chance to mitigate the greenhouse effect. This has resulted in the emergence of idea of “sustainable tansportation” or ”sustainable mobility”. To a high extent, mobility can be organized very effectively on the basis of public transportation and non-motorized modes.

2. THE CONCEPT OF SUSTAINABLE TRANSPORTATION

2.1 What is Sustainable Development

The term ”sustainable development” was first mentioned in 1980 in the report World Conservation Strategy of the International Union for Conservation of Nature and National Resources (IUCN). In 1987, the World Commission on Environment and Development (WCED) described the concept of sustainable development more extensively in a report entitled ”Our Common Future ” which is often named “the Brundtland Report”. In the Brundtland Report sustainable development is defined as: *The development that meets the needs of the present without compromising the ability of future generation to meet their own needs*.

Although there exist diversity of descriptions of sustainable development, it is almost accepted that the concept of sustainable development has evolved to encompass trade-offs among the different objectives of the three pillars: the social system (institutional change); the economic system (investments and technological development) and the environmental system (the exploitation of resources) [1].

For example, Munasinghe [2] identifies three different aspects of sustainable development that interact to produce the complexity of weighing costs and beneficiaries, i.e. the economic determinants, the environmental determinants and the socio-cultural determinants. The interaction between the three systems is shown in Fig. 1. To find the right balance between the three objectives has become one of the main research topics of present decision-making methodologies.

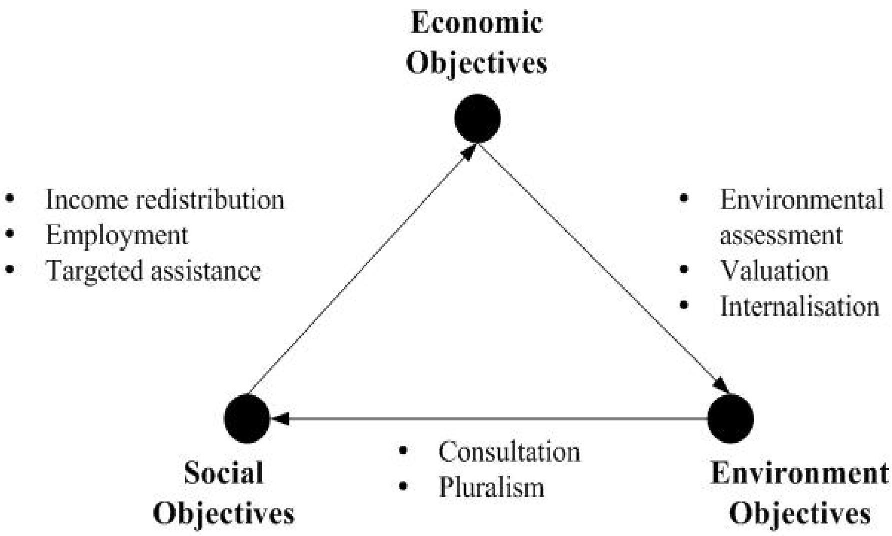

Figure 1. Three Main Objectives of Sustainable Development (Source: [2])

2.2 What is Sustainable Transportation

There is no universally accepted definition of sustainable transportation. However, a broader definition of sustainable transportation - "*satisfying current transportation and mobility needs without compromising the ability of future generations to meet their own needs*" deriving from the three main objectives defined above is uncontested. The criteria for the sustainable transportation thus can be: 1) the extent of satisfying transportation demand, the technical and commercial feasibility of the transportation technology, etc. (i.e. economic objectives); 2) the production and regeneration functions, etc. (i.e. environmental objectives); and 3) cultural richness, institutional factors, social equity, etc. (i.e. social objectives).

After reviewing related references sustainable transportation in this paper is defined as : *The achievement of continued transportation activities supported by environmental, economic and social objectives at various space-based scales of operation*.

The key strategies on a general level (national, state and regional level) which mark the "regulatory framework" toward sustainable transportation are:

- Reduction of space consumption;
- Concentration of development –"compact city";
- Reduction of motorized traffic;
- Encouragement of alternative transportation modes, especially public transit systems;
- Introduction of technology innovations to manage travel demand.

2.2 How to Measure Transportation Sustainability

Even though transportation sustainability is not defined objectively and unambiguously, interest has grown in developing qualitative or quantitative methods to measure transportation sustainability over the past two decades. Many debates and studies about the measurement of transportation sustainability do not define, or even derive a common understanding, about what is to be measured. However, measures of transportation sustainability at present tend to be an amalgam of economic, environmental and social indicators to track trends, compare areas and activities, evaluate particular policies and planning options, and set performance targets.

There are two basic approaches to measure transportation sustainability problem solving. A qualitative approach uses frameworks - sets of organizing principles - and uses descriptive statements to characterize transportation systems and their behaviors. A quantitative approach is based on models defined by the language of mathematics and uses measurable indicators to assess and valuate the status of transportation development. In order to measure and monitor economic, social and environmental factors affecting transportation activities, only the quantitative approach is discussed in this paper since results of many studies show that quantitative models may be very useful in the transportation planning sense [3].

3. THE CONCEPT OF QUANTITATIVE MODELS

3.1. Assessment Indicator Models

There are three types of the indicator models: 1) the composite index model; 2) the multi-level index model and 3) the multi-dimension matrix model. A brief introduction is described below [4]:

3.1.1. Composite Index Model

The output of the composite index model is a single index representing degree of satisfying economical, social and environmental objectives. Similar composite indices such as Green Gross National Product (GNP), Index of Sustainable Economic Welfare (ISEW), Ecological Footprint, etc…are often used to measure the sustainability. However, a universal and single composite index of sustainable transportation is difficult to obtain.

3.1.2. Multi-level Index Model

The multi-level index model is mainly composed of a series of indicator variants indicating different goals and objectives. This model shown in Fig.2 is especially used frequently in China [5].

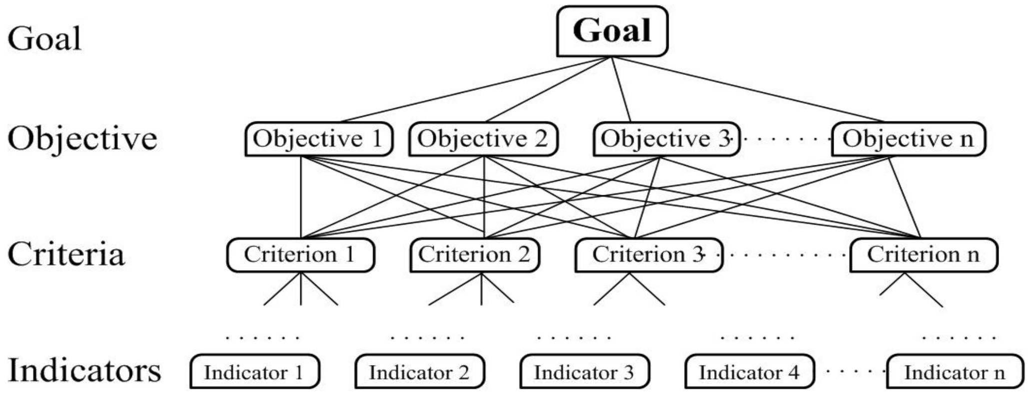

Figure 2. Multi-level Index Model

3.1.3. Multi-dimension Matrix Model

The multi-dimension matrix model shown in Fig.3 describes interactions among different indicators by using logic architectures. In the early 1990s, the most famous logic architecture such as the Pressure-State-Response (PSR) framework, was accepted by many agencies and even now is put into practice. Indicators are used as powerful tools to help identify, monitor and support PSR relationships. This approach has formed the basis for ongoing developments of the Driving–Force–State-Response (DSR) and the Driving-Force, Pressure-State-Impact-Response (DPSIR) frameworks. And thus, indicators of sustainable transportation can be derived from these logic architectures.

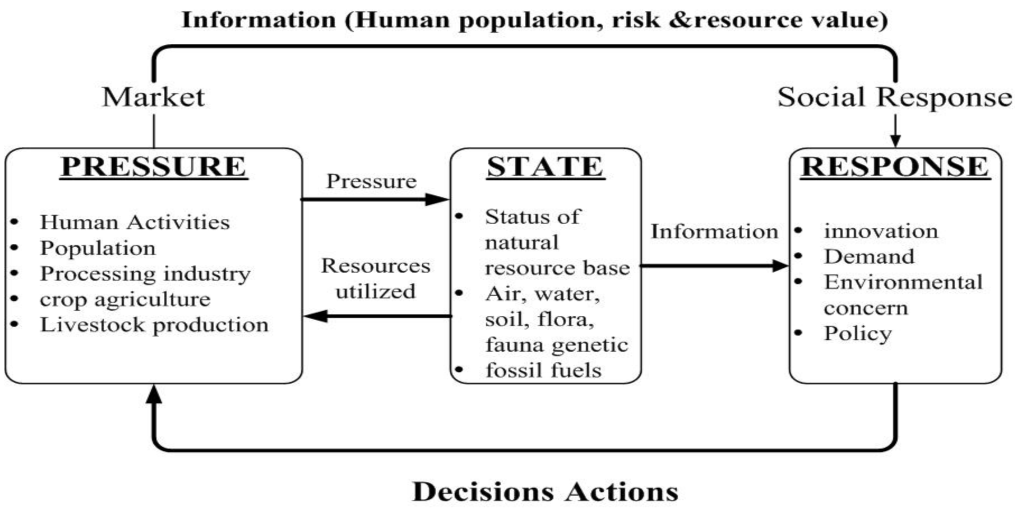

Figure 3. An Example of Multi-dimension Matrix Model (PSR Model)

3.1.4. Summary

In order to measure the transportation sustainability, results of many studies show that the multi-level indicator model is used most frequently [4]. The process of measuring transportation sustainability is shown in Fig.4 and described as followings:

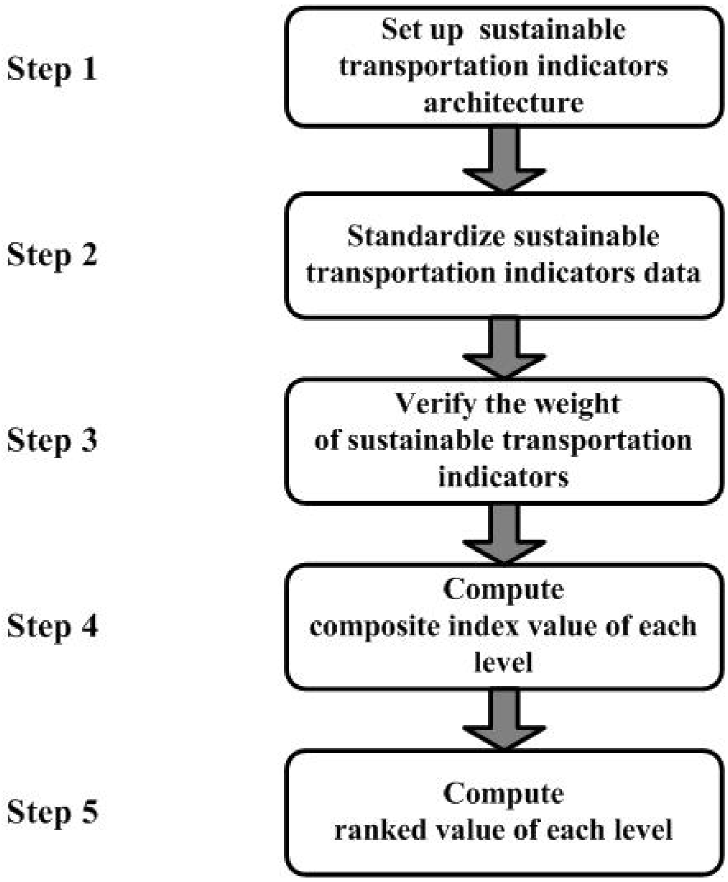

Figure 4. Process of Measuring Transportation Sustainability

1) Step1: Set up the sustainable transportation indicators architecture

Depending on development status of each country, sustainable transportation indicators are derived from the economic, social and environmental goals, objectives and criteria and classified in the form of multi-level architecture.

2) Step2: Standardize sustainable transportation indicators data

The purposes of this step are to find differences among each indicator within the same year and to compare changes of indicators through the observed period. Standardization methods are often used to convert raw data of positive and negative indicators into certain numerical ranges within a given interval. The results represent better, worsen, or steady-state status of indicators based on social, economic and environmental dimensions during the observed period. The formula is shown below:

$$Positive\ indicators: \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (1)$$

$$Negative\ indicators: \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (2)$$

$x_i^{(0)}(k)$: original indicator value; $\min x_i^{(0)}(k)$: minimal indicator value; $\max x_i^{(0)}(k)$: maximal indicator value.

3) <u>Step3: Verify the weight of sustainable transportation indicators</u>

The purpose of this step is to identify the importance of each sustainable transportation indicator. The Delphi, Analytic Hierarchy Process (AHP), Entropy and Principle Factor Analysis are common methods to measure relative preferences of the decision maker when one indicator is compared with another one.

4) <u>Step4: Compute composite index value of each level</u>

A composite index is derived to assess the status of transportation development. Depending on indicator standardization values in Step 2 and indicators weights in Step 3, the composite index value of each level is computed separately by the following formula:

$$CI = \sum_{i=1}^{n} W_i CI_i \quad (3)$$

CI : composite index value; n: number of composite index; W_i : weight of i composite index; CI_i: value of i composite index.

5) <u>Step5: Compute sustainability ranked value of each level</u>

A ranked value is then computed to valuate the transportation sustainability. The composite index value of each level is converted into ranked value by the rate-score method. The formula to compute sustainability ranked value of the level of goal is shown below:

$$CI_{(t)} = \sum_{l=1}^{n} W_l CI_{l(t)} \qquad \sum_{l=1}^{n} W_l = 1 \tag{4}$$

$$\Delta CI_t = CI_{(t)} - CI_{t-1} \tag{5}$$

$$\sum \Delta CI_{(t)} = \Delta CI_{(t)} + \sum \Delta CI_{(t-1)} \tag{6}$$

$$SRV_{(t)} = \frac{\sum \Delta CI_{(t)}}{T_t - 1} \tag{7}$$

$CI_{l(t)}$: composite index value of level of objectives; $CI_{(t)}$: composite index value of level of goal; W_j : composite index weight of each level of objectives; $\Delta CI_{(t)}$: composite index changeable value of level of goal; $SRV_{(t)}$: sustainability ranked value of level of goal; t = present year ; $T_{(t)}$: year responding to t.

3.2. System Analysis or System Dynamics Models

Assessment indicator models lack a feedback mechanism if the impacts on environmental or social or economic dimensions occur. A comprehensive approach to measure transportation sustainability is to use system analysis or system dynamics models. Specifically, it is about how environmental, economic, and social systems interact to their mutual advantages or disadvantages at various defined scenarios.

System dynamics models have been applied in the bio-cybemetic experiments regarding the social impacts of industrial and transportation development. The concept of system dynamics models is based on relationships between state and flow variables organized in feedback loops. In such a setting, these models can design and evaluate a cause-and-effect relationship within an integrated sustainable transportation system.

In the following example [6], a sustainable transportation system can be defined as the one that is integrated with the economic, social and environmental dimensions through vertical and horizontal linkages which is shown in Fig. 5. Since transportation is a substantial contributor to economic growth, it is possible to define that transportation networks are subsystems of regional economic system. On the other hand, regional economic systems also are subsystems of macro economic system. These three internal levels describe vertical linkages of a sustainable transportation system within economic dimension. In addition, horizontal linkages include social and environment implications of the sustainable transportation system.

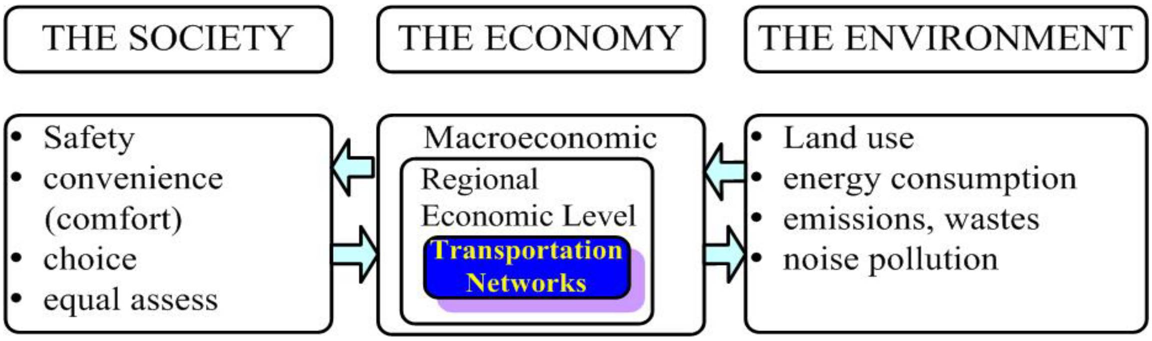

Figure 5. Vertical and Horizontal Linkages of Sustainable Transportation System (source: [6])

Both of linkages are captured by intrinsic dynamics which was decided from the relationship between state and flow variables. That means any variables changes in the vertical linkage would reflect horizontal linkages and resulted in a sustainability shift of sustainable transportation system. Then, sustainability standard is a critical part of meeting the goals of a sustainable transportation system. The system dynamics flow chart of a sustainable transportation is shown in Fig. 6.

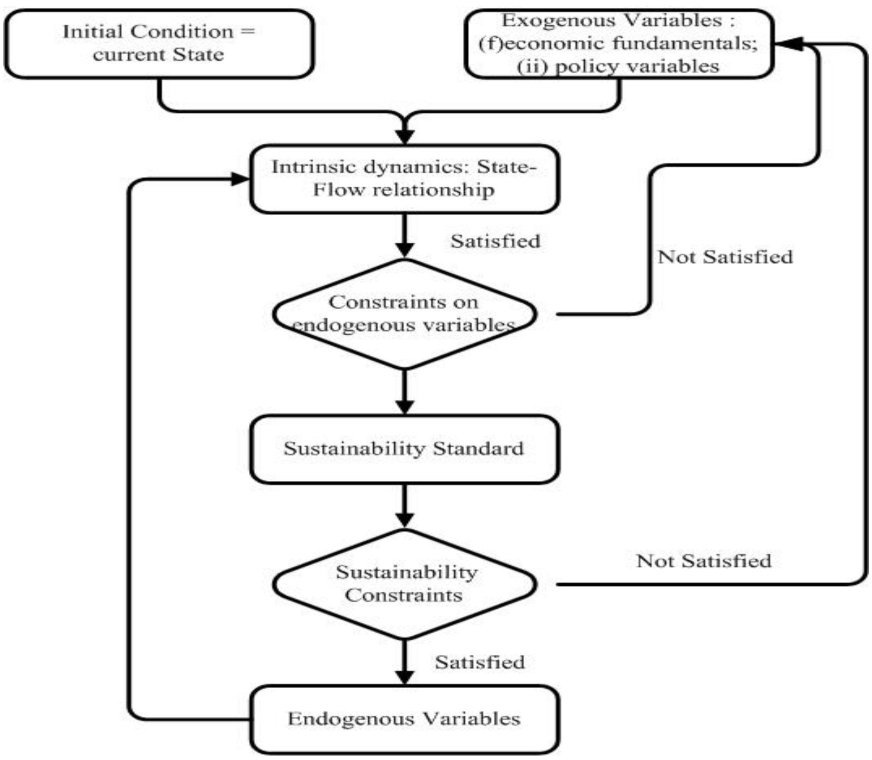

Figure 6. System Dynamics Flow Chart of Sustainable Transportation

With respect to intrinsic dynamics, the characteristics of a complex system can be described in the form of mathematical functions. To implement this model and obtain all possible different scenarios results, it is strongly recommended to use computer simulation programs (for example, DYNAMO, STELLA, etc.).

3.3. Optimization Models

A mathematical optimization model consists of an objective function and a set of constraints in the form of a system of equations or inequalities. Optimization models are used to solve extensively in almost all areas of decision-making, such as engineering design and financial portfolio selection to real world problems. In the problem solving of sustainable transportation, an optimization model attempts to find an optimal solution under the constraints of the social, economic, and environmental objectives. The approach of linear programming is used most frequently.

In the following example [7], the optimization model attempts to find an optimal solution of urban traffic structure under social, economic, ecological and resources constraints. The concept of ecological negative effects is especially emphasized on this model. The objective function is to minimize negative ecological effects (N) and investment of infrastructure (I) (equation 8) that is subject to “travel demand less or equal to designed capacity (equation 9)”; “affordable travel cost (equation 10)” and “limit value of heat island effect (equation 11)”.

$$Min\ f(N,I)=\left\{\sum_{j=1}^{J}\sum_{i=1}^{I}(D_j R_{ji}(P)E_{ji}),\sum_{j=1}^{J}\sum_{i=1}^{I}(C_{ji}s_{ji})\right\} \tag{8}$$

$$s.t.\quad Cap_{ji}-D_j R_{ji}(P)\geq 0,\ j=1,2,\ldots,J;\ i=1,2,\ldots,I \tag{9}$$

$$P_m \geq P_m - P \geq 0; \tag{10}$$

$$Whot-\sum_{j=1}^{J}\sum_{i=1}^{I}H_{ji}\bullet s_{ji}\geq 0 \tag{11}$$

$$s_{ji}\geq 0,\ j=1,2,\ldots,J;\ i=1,2,\ldots,I$$

s_{ji}: planning capacity of i mode in OD j pair; P: travel cost vectors which reflect the transportation management policies; D_j :travel demand of people and goods in OD j pair; $R_{ji}(P)$:probability of choosing i mode in OD j pair; E_{ji} :coefficient of negative ecological effects of i mode in OD j pair; C_{ji}: hardware and software cost of i mode in OD j pair; Cap_{ji}: designed capacity of i mode in OD j pair; P_m: affordable travel cost; $Whot$: limit value of heat island effect; H_{ji} : coefficient of heat island effect of i mode in OD j pair .

Liu (2001) [8] computed the optimal proportion of mode utilization and compared with current status to obtain a gap value by using linear programming. Then sustainability is classified into 5 grades: A, B, C, D, and E. The smaller the gap, the better the sustainability. It was found that the increase of proportion of public transportation could achieve a higher grade of transportation sustainability.

3.4. Summary

Assessment indicator models, system dynamics models and optimization models are reviewed and summarized in Table 1. The multi-level index model within the assessment indicator models, however, is used most frequently.

Table 1. Summary Description of Sustainable Transportation Assessment Models

Assessment Models		**Methodology**	**References**	**Indicators Display**	**Valuation**
Assessment Indicator Models	Composite index model	-	-	-	-
	Multi-level Index Model	Linear weighted Method	S.T, Lee (2000)	Qualitative	No
			Yang, H (2001)	Qualitative	No
			C.C. Hung (2002)	Quantitative	Yes
	Multi-dimension Matrix Model	Criterion-Influence-Action -Measures computer model	Canada-Ontario round table (2001)	Qualitative	No
System Dynamics models		System; Neural Network	Yuri Yevdokimov (2002)	Quantitative	Yes
Optimization Models		Linear Programming	C.Y, Chiang and H.K, Yang, (1998)	Quantitative	No
		Linear Programming	C.Y, Liu (2001)	Quantitative	Yes

4. CASE STUDY

There is a tension between convenience and comprehensiveness when selecting quantitative models mentioned above. A smaller set of indicators using easily available data is more convenient to collect and use, but may overlook important impacts. A larger set of indicators can be more comprehensive, but may have unreasonable data collection costs and be difficult to interpret. Considering data requirements and availability the multi-level index model is chosen and used to assess and valuate transportation sustainability by taking Taiwan as the case study in this paper.

4.1. Multi-level Indicators Model of Sustainable Transportation in Taiwan

4.1.1. Set up the Framework of Indicators

Referring to the UN's DPSR framework, many indicators related to sustainable transportation are chosen and ranked with priorities based on the conclusions of expert researches and the results of surveys worldwide. Some indicators have to be deleted due to insufficient data, while some were combined due to high correlation with others. And then indicators in multi-level indicators model are set up according to the framework of goal, objectives, and criteria of Taiwan's Transportation Whitepaper [9].

4.1.2. The Standardization of Sustainable Transportation Indicators Data

The data for these chosen indicators are collected from various statistics annual reports of public authorities from the year 1990 to year 2001 which are summarized in [10]. The standardization method is used to convert raw data of positive and negative indicators into [0,10] interval. If value of the indicator approaches to 10, that means the status of this indicator within 11 years is getting better, otherwise, it means getting worse. The results show the indicator trend for social dimension is better than economic and environmental dimensions over the past 11 years. The weakest status is in the environmental dimension.

4.1.3. Verify the Weights of Sustainable Transportation Indicators

The Analytic Hierarchy Process (AHP) method is then used as the subjective analysis to identify the weights of indicators. 40 questionnaires are distributed to relating private companies, public authorities and academic scholars. The results based on 33 effective samples show that the environmental indicators are endowed with highest weights. Besides, the results also show that the most important indicators for social, economic and environmental criteria are " number of deaths in car accidents per million vehicle kilometers", "average load factor of public transportation" and "number of days which pollution standard index > 100", respectively.

4.1.4. Compute the Composite Index Value of Each Level

The composite index value (CI) of sustainable transportation for social, economic and environmental dimensions are shown in Fig. 7, 8 and 9 respectively. It is shown that the transportation development in Taiwan from the social dimension achieves the highest value (8.26) in 2000, from the economic dimension achieves the highest value (6.54) in 1998, and from the environmental dimension achieves the highest value (6.62) in 1998. In Fig. 10, the highest CI value (6.49) for sustainable transportation in Taiwan occurred in 1998.

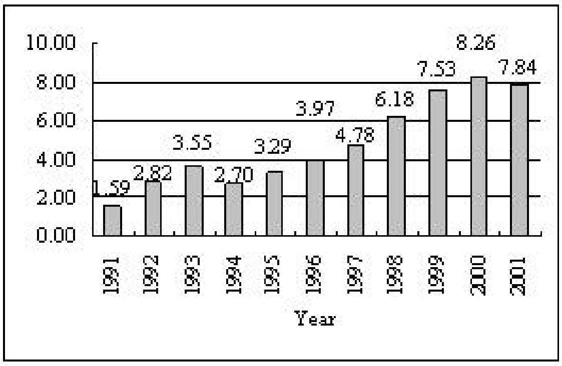

Figure 7. CI of Social Dimension

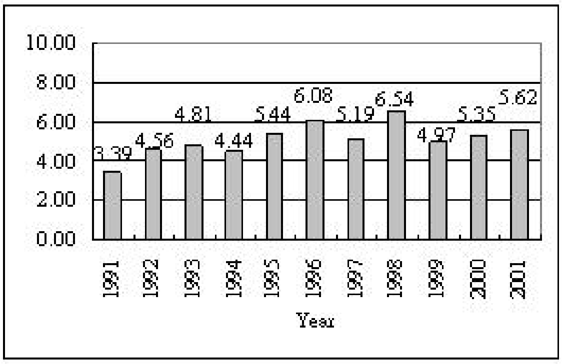

Figure 8. CI of Economic Dimension

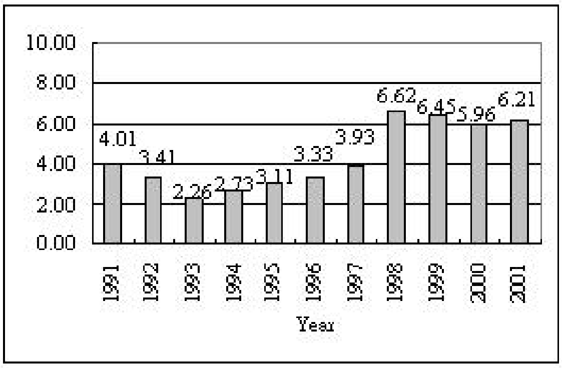

Figure 9. CI of Environmental Dimension

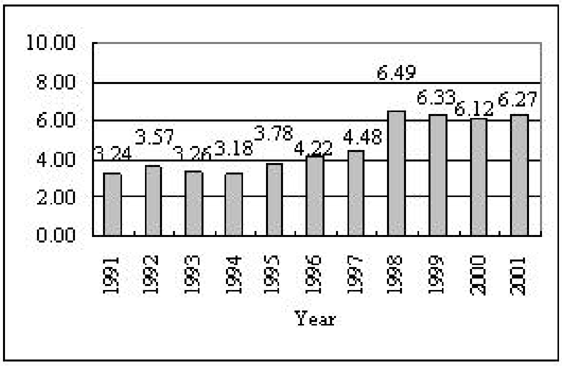

Figure 10. CI of Sustainable Transportation

4.1.5. Compute Sustainability Ranked Value (SRV) of Each Level According to the Classification of Sustainability Grade

1) The classification of sustainability grade

Referring to the results of Hung's (2002) thesis [11], four types of transportation sustainability grades stand for different states - unsustainability, weak sustainability, medium sustainability, strong sustainability - shown in Table 2. For example, if a sustainability ranked value (SRV) is computed to be a value of 0.43, that means the sustainability state is weak. The purpose of this classification is to provide monitoring signals representing the state of transportation sustainability in Taiwan.

Table 2. Classification of Sustainability Grade

Sustainability Grade	**(-∞,0]**	**(0,0.5]**	**(0.5,1]**	**(1,+∞)**
Sustainability State	Unsustainability	Weak Sustainability	Medium Sustainability	Strong Sustainability

2) Results of Sustainability Ranked Value (SRV)

The sustainability ranked value (SRV) of sustainable transportation for social, economic and environmental dimensions are shown in Fig. 11, 12, 13 respectively. It is shown that the transportation sustainability from social dimension is between weak and medium state; from economic dimension is in weak state; from environmental dimension remains in weak state until 1998. As shown in Fig.14 the worst transportation state (unsustainability) in Taiwan occurred in 1994.

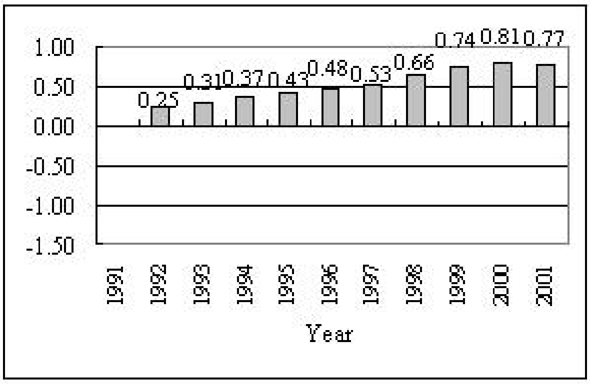

Figure 11. SRV of Social Dimension

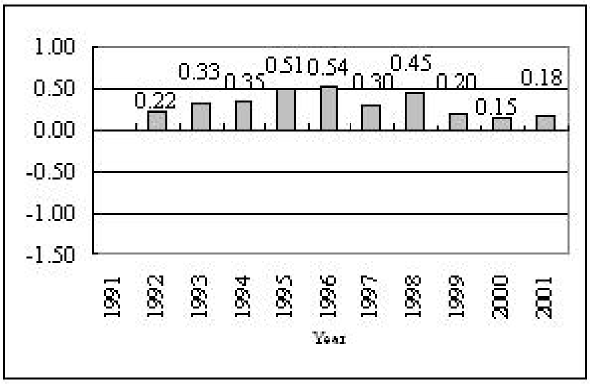

Figure 12. SRV of Economic Dimension

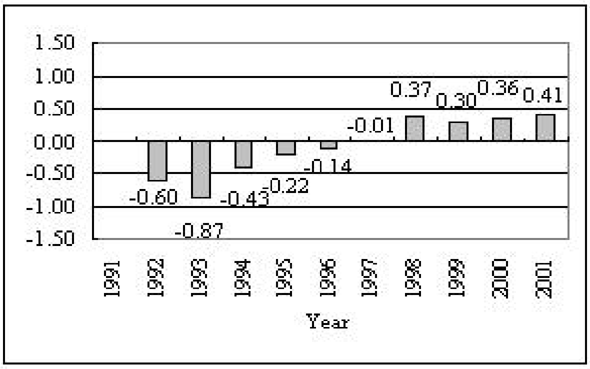

Figure 13. SRV of Environmental Dimension

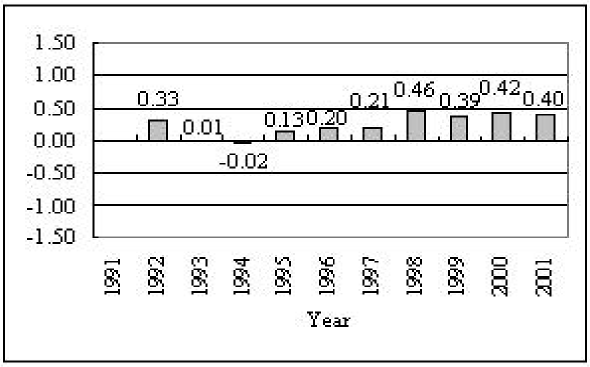

Figure 14. SRV of Sustainable Transportation

4.2. The Development of a Simplified Policy Mechanism

A simplified policy mechanism is developed to identify appropriate strategies corresponding to those indicators with weak sustainability. In Fig. 15, the smallest SRV is found from social, economic and environmental dimensions. Referring to the weakest dimension above, the weakest criterion is searched with the smallest SRV. And then, referring to the weakest criterion above, the results of indicator weights are subsequently used to give the priorities of corresponding indicators that need to be improved. Finally, appropriate strategies with respect to improved indicators are recommended.

For example, the worst state of transportation development in Taiwan occurred in 1994 (see Fig. 14). And it is found that the state of transportation development from the environmental dimension is unsustainable in 1994. From the environmental dimension, the criterion "environmental protection" has the smallest SRV. Examining the results of indicator weights, the indicator that should be given the first priority is "number of days which pollution standard index > 100". Therefore, a strategy such as implementation of mobile exhaust gas surveillance can be recommended as the appropriate one for this case.

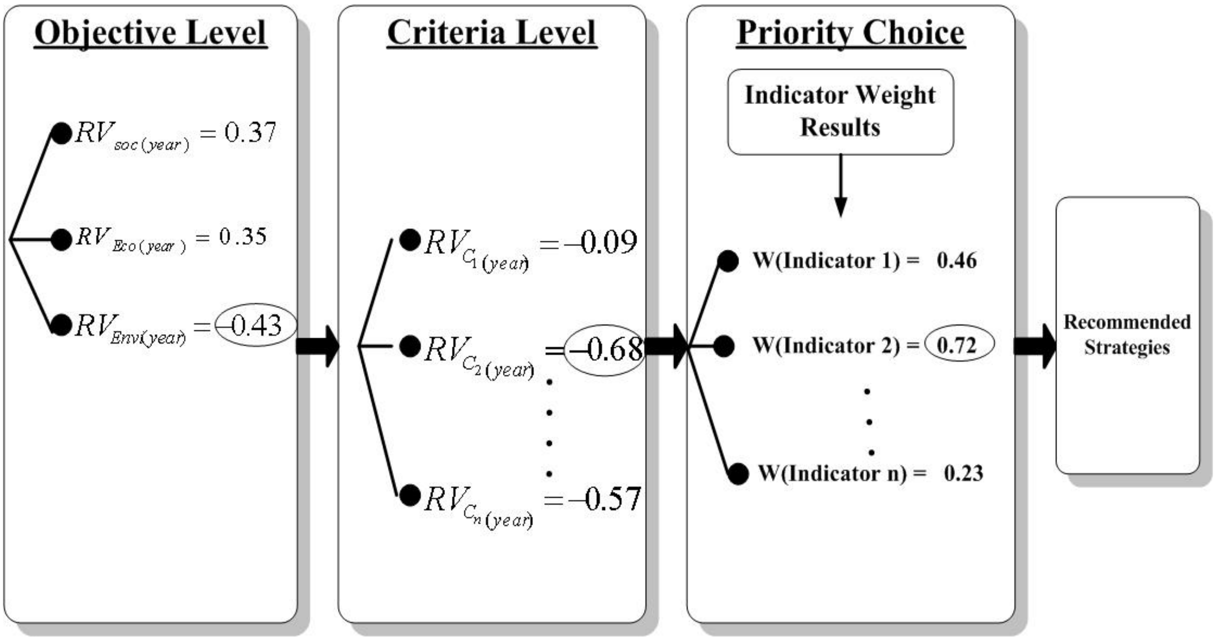

Figure 15. A Simplified Policy Mechanism for Identifying Recommended Strategies

5. CONCLUSION

Sustainable transportation is one of the main research topics in the field of transportation science. There are basically two approaches to measure transportation sustainability at present, i.e. the qualitative models and the quantitative models. In this paper, three quantitative models: assessment index models, system dynamics models and optimization models are discussed. Despite of advantages and drawbacks of different models, assessment index models are still the most frequently approach for sustainable transportation studies at the initial stage. However, there is a tension between a smaller set and a larger set data collection when selecting assessment index models. Therefore, the data requirements and availability are the key factors for choosing appropriate models.

REFERENCES

1) Tao, C.C. and Hung, C.C (2002) The Role of Urban Mass Rapid Transit for Sustainable Transportation, **Proceedings of 2002 World Metro Symposium,** Taipei, Taiwan, April 14-19, 2002.
2) MacKenzie, J. and Walsh, M (1990) Driving Forces: Motor Vehicle Trends and their Implications for Global Farming, Energy Strategies and Transportation Planning, World Resources Institute Washington, Washington.
3) Gu, K. and Young, W. (1998) Verifying and Validating A Land Use-Transport-Environment Model, **Transportation Planning and Technology, Vol.21**, 181-202.
4) Tao, C.C. and Hung, C.C (2002) Comments on Quantitative Methodologies of Urban Sustainable Transportation (in Chinese), **2002 Cross-Strait Conference on Urban Transportation**, Kunming, China, August 16-19, 2002.
5) Yang. H (2001) **Sustainable Development of Transportation System (in Chinese)**. China Railway Publication, Beijing.
6) Yuri Tevdokimov (2002) Sustainable Transportation System: A System Dynamics Approach, **International Conference on Public Economic Theory**, Paris, France, July 4-6, 2002.
7) Chiang, C.Y and Yang, H.K (1998) A Research on Sustainable Development of Urban transportation system (in Chinese), **Shanghai International City Traffic Construction & Management Seminar**, Shanghai, China, November 25-26, 1998.
8) Liu, C.Y (2001) Optimization Mode Proportion of Sustainable Transportation. M.S. Thesis of Civil Engineering, National Taiwan University, Taiwan.
9) Institute of Transportation (2000) Transportation Whitepaper (revised edition). Ministry of Transportation and Communications, Taiwan.
10) Institute of Transportation (2002) Quantitative Indices of Sustainable Transportation. Report No. MOTC-IOT-90-TB02, Ministry of Transportation and Communications, Taiwan.
11) Hung, C.C (2002) A Study on Assessment and Valuate on Sustainable Transportation in Taiwan. M.S. Thesis of Transportation Science, Tamkang University, Taiwan.