Towards An Informatics Framework for Sustainability Analysis in Urban Transportation Planning

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ABSTRACT

An informatics framework for sustainability analysis in urban transportation planning is developed in this paper. The framework consists of sustainability indicators, structured impact analysis, a general procedure, and a conceptual informatics framework which organizes all these elements in a decision support system. In deriving sustainability indicators and structuring impact analysis, specific attention is given to comparisons between a trip-based approach and an activity-based approach, so that drawbacks of the conventional trip-based approach and potential of the activity-based approach are manifested in the context of sustainability analysis. Implications to the design of a decision support system for sustainability analysis are also discussed in terms of database and model base designs.

1 INTRODUCTION

Wang, et al. (1995) proposed a conceptual framework for defining sustainable development of urban transportation. They defined that: sustainable development of urban transportation is promoted by the 'correct' combination of policies, technologies, and people's behaviour to integrate social and economic principles with environmental concerns so as to simultaneously achieve:

- efficiency of system operation to save travel time and release traffic congestion;
- effectiveness in providing transport services, measured in terms of transport users' benefits;
- economic viability in sustaining the operation of the transportation system, in terms of economics and finance;
- social equity in the distribution of transport services, costs and negative impacts (e.g. traffic noise); and
- environment sustainability through relevant measures so that to reduce (1) the use of scarce and non-renewable resources, e.g. fossil fuels and land, and (2) the emissions of CO₂ and harmful substances.

It follows that the objectives of transport policies should be in accordance with these lines, and the sustainability of transport policies should be evaluated along these five
dimensions, i.e., efficiency, effectiveness, economic viability, social equity and environmental sustainability. The conceptual framework provides the basic notions regarding the meaning, the dimensions and problem boundaries of sustainability and sustainable development. They are abstract and qualitative in nature, however. In order to apply this conceptual framework in planning and policy making routines, it is necessary to operationalize it into a tangible evaluation framework and manageable indicators.

We will introduce in this paper a concept of sustainability analysis in urban transportation planning. The proposed concept will be further developed into an informatics framework, which can be used as a conceptual model to develop a decision support system. The first section will present a general framework for sustainability analysis. This is supposed to provide a theoretical base for the framework to be developed in this paper. The next section is dedicated to the development of this framework. It begins with presenting different approaches, followed by the discussion of structured impact analysis, sustainability indicators and aggregation and combination of indicators. Data and model requirements are then presented in the next two sections. Next, justifications of why to adopt a decision support approach and how the informatics system can be designed are discussed. The final section presents conclusions and further research orientations. All discussions are limited to transportation of passengers, the case of goods transport is not included.

2 A GENERAL FRAMEWORK FOR SUSTAINABILITY ANALYSIS

Sustainability analysis is basically an evaluation process, in which sustainability is a key criterion. Nijkamp (1995) argued that any sustainability analysis should contain three components, they are:

- the identification of a set of sustainability indicators;
- a structured impact analysis methodology; and
- the identification of a set of normative reference values.

Indicators "...basically provide a way of transforming the raw data into meaningful information which can be used for measurement and comparison" (Bertuglia and Rabino, 1994). Sustainability indicators are used to measure the relevant dimensions of sustainable development in the concerning fields. The selection of indicators is a critical step in the whole process of sustainability analysis. The criteria for selection of indicators were summarized by Carley (1981) as:

- appropriateness and validity;
- uniqueness, accuracy and reliability;
- completeness and comprehensibility;
- controllability;
- reasonable cost for data collection; and
manageable feedback time, so that information can become available within the
time frame necessary for decision-making (Clarke and Wilson, 1994).

The structured impact analysis methodology incorporates domain models which
predicts impacts of plans or policies in question, so that scores of sustainability
indicators can be generated. These scores are the basic information for evaluation. The
identification of a set of normative reference values is to provide a stickyard for
evaluation. It is not always easy to identify normative reference values which have
absolute meaning, such as environment carrying capacity, critical levels at which
irreversible environmental decay occurs, and so on, given the constraints of scientific
knowledge in regarding fields. However, it is not always that one is asked to give
judgments on whether a system is sustainable or not, in many cases, you will be asked
that if certain plans or policies are implemented, what are their impacts in terms of
sustainability. Therefore, comparison is the main focus, for example, comparisons
between plans or between the case of intervention and the case of no-intervention, etc.
The normative reference values are not relevant in this context, only the differences
between indicator scores of alternative actions.

While the presented framework contains the major components, other elements need
to be included as well. Because evaluation can be implemented from different
perspectives, such as different spatial units and sectors, etc., it is normally required to
aggregate scores of indicators from small units to larger units, and to combine
indicators of different dimensions to generate integrated index. Therefore, it is
necessary to expand this framework to include these elements as well.

Figure 1: A General Framework for Sustainability Analysis

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<table>
<thead>
<tr>
<th>Sustainable Concepts</th>
<th>Impact analysis</th>
<th>Policies Plans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria to judge</td>
<td>Evaluation</td>
<td>Aggregation Combination</td>
</tr>
<tr>
<td></td>
<td>Sustainable performances in different contexts and from various perspectives</td>
<td></td>
</tr>
</tbody>
</table>
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Figure 1 presents such an extended general framework for sustainability analysis. By evaluation we refer to transform outcomes from impact analysis to indicators. Models for calculating indicators are required at this stage, we can term them evaluation models. The indicators can be further processed by aggregation and combination, so that the information on sustainable performances in different contexts and from various perspectives can be obtained. By aggregation, indicator scores at lower units can be aggregated into larger units in terms of space or sector. Combination aims to produce general index by combining different indicators into a single index. The combining rules can be any method in the family of multi-criteria analysis, depending on the objectives and views of intended users.

3 SUSTAINABILITY ANALYSIS IN URBAN TRANSPORTATION PLANNING AND POLICY MAKING

The general framework developed in the last section provides guidelines to formulate a framework for sustainability analysis in urban transportation planning and policy making. We will develop this framework along these guidelines in the next subsections.

3.1 Approaches

Different academic paradigms offer different approaches for policy analysis, because they have different perceptions regarding problems and solutions to problems. As explained by Jones (1995), “Any paradigm used in the policy arena not only affects the perception of problems and the generation of policy options, but also the evaluation of options, including: the dimensions on which options are evaluated and the weighting given to different factors.” Nowadays, researchers intend to distinguish a trip-based approach from an activity-based approach in the field of transport research. These two approaches make different assumptions regarding people’s travel behaviour. They thus provide different simulation models. On the other hand, they have different perceptions over benefits and costs of transport activities. Therefore, different evaluation indicators can be derived.

3.2 Structured Impact Analysis

In most cases, the implementation of plans or policies is expected to cause changes to the nature and structure of traffic flows, in terms of volume, spatial, temporal and modal distribution, etc., observed in disaggregate and aggregate forms. These changes are the basic information for evaluation. Evaluation results depend primarily on how accurately these changes can be predicted. The accuracy of prediction depends on how modeling approaches are able to correctly simulate people’s travel behaviour changes resulting from implementation of policies. The trip-based approach is unable to
capture the whole range of behaviour changes, the approach might also over or under predict changes, because it can not capture the interrelationships between trips and between individuals. On the other hand, the activity-based approach recognizes the interrelationships between trips, between trip and activity and between individuals of the same family. It is able to simulate the whole range of behaviour changes of an individual and of a whole family. Basically, these two approaches have different views about travel behaviour changes, as illustrated in figure 2 and 3. Also, the focus on travel only of the trip-based approach limits its ability to simulate some kinds of policies, which are implemented in the fields other than transportation, e.g., changing opening hours of shops, while the activity-based approach has potentials to overcome this limitation.

Nevertheless, the trip-based approach offers a complete set of models for simulation, it has been institutionalized in transportation planning agencies for decades. On the other hand, the activity-based approach is still at its infant stage of development. Although attempts and progress have been made in recent years, such as, the so-called TRANSIMS (Transportation Analysis and SIMulation) System which is under development by the Los Alamos National Laboratory (LANL) in Santa Fe, NM, U.S.A, it is generally agreed that much efforts are still required for the approach to be developed into its full swing.

Therefore, in structuring the impact analysis, we suggest to keep the structure of the trip-based approach, but adopt a supplementary way to combine models of these two approaches, so that, the limitations of the trip-based approach models can be overcome by models of the activity-based approach.
3.3 Sustainability Indicators

Evaluation of transport plans and policies has been a complex issue in terms of the use of indicators. Although in general a cost-benefit analysis procedure is used and travel time savings is a common used benefit indicator, other indicators used are normally different from case to case, upon objectives to be pursued. In general, there is no a systematic framework of indicators.

We attempt to develop indicators to measure the five dimensions of sustainable development, as defined in the introduction section. Five categories of indicators can be distinguished, i.e., indicators for measuring system operation; user benefits, economic viability; social equity and environmental sustainability, respectively. In this way, these indicators form a framework to measure sustainability.

As stated above, the trip-based and activity-based approaches offer different perceptions over transport costs and benefits. Therefore, in deriving the indicators framework, we will keep our mind open for both approaches while applicable. Table 1 presents the framework in a way of comparison between the trip-based and activity-based approaches. We will examine them category by category.
Table 1: A Framework of Indicators to Measure Sustainability

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>TRIP-BASED INDICATORS</th>
<th>ACTIVITY-BASED INDICATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>system performance (efficiency)</td>
<td>number of trips and trip-kilometers by mode, time of day, area and person type, level of service (or vehicle speed and traffic volume) by link, and patronage of public transport, etc.</td>
<td>number of trips and trip-kilometers by mode, time of day, area and person type, level of service (or vehicle speed and traffic volume) by link, and patronage of public transport, etc.; disruptions to the implementation of planned activity schedules</td>
</tr>
<tr>
<td>user benefits (effectiveness)</td>
<td>accessibility (travel costs; spatial opportunities and consumer welfare indicators)</td>
<td>total discretionary time available; flexibility to perform activities and expected maximum utility of alternative activity schedules</td>
</tr>
<tr>
<td>social equity (acceptability)</td>
<td>variance (Gini coefficient, mean deviation, Theil’s entropy index) of user benefits and environmental costs among different locations or social groups</td>
<td>variance (Gini coefficient, mean deviation, Theil’s entropy index) of user benefits and environmental costs among different locations or social groups</td>
</tr>
<tr>
<td>environmental sustainability</td>
<td>environmental emissions and energy consumption per day (year, car, etc.) by area</td>
<td>environmental emissions, and energy consumption per day (year, car, etc.); time/person exposure to noise; time/person exposure to harmful emissions.</td>
</tr>
<tr>
<td>economic viability</td>
<td>total capital costs required and expected annual operating costs, etc.</td>
<td>total capital costs required and expected annual operating costs, etc.</td>
</tr>
</tbody>
</table>

Indicators measuring system performance include number of trips and trip-kilometers by mode, time of day, area and person type, vehicle speed and volume by link, and patronage of public transport, etc. The performance of particular links of the transport network is normally evaluated by the indicator of ‘level of service’. ‘Level of service’ is jointly determined by volume and average speed of traffic flow, road capacity, and safety, etc. These indicators can be calculated on the basis of either traffic statistics (for evaluating performance of existing systems) or prediction data (for assessing policy impacts). These indicators are unique to either the trip based approach or the activity-based approach, but the two approaches can give different indicator scores in the case of assessing policy impacts, because they have different simulation models which give different predictions. Also, in the case of activity-based approach, some other indicators like disruptions to the implementation of planned activity program
can be used to measure system performance such as congestion, e.g., number of planned activities being canceled due to congestion.

Indicators of user benefits are used to measure how people are served by transport system, in terms of accessibility or other terms. They can be defined for different groups of people (classified by income or other variables) in several contexts, e.g., living in a particular location, using a particular route or transport mode, etc. Since the trip-based approach and the activity-based approach have different views over travel, as stated above, they provide different perceptions about where the benefits or costs should be associated with, trips or activities. Therefore, the trip-based approach defines accessibility as travel costs or spatial opportunities provided by transport service. On the other hand, the activity-based approach views travel in the context of activity participation, it defines accessibility as opportunities of successfully implementing people’s activity programs. In this way, the derived nature of travel is explicitly recognized. Wang and Timmermans (1996) discuss these issues in more details.

Environmental sustainability is evaluated by indicators of energy consumption (e.g., fuel consumption) and environmental emission (e.g., CO₂, CO emission). These indicators are derived from data on status of motorized traffic flows (volume, speed, and type of vehicles, etc.). Like the indicators of system performance, these indicators can be calculated on the basis of either traffic statistics (for evaluating performance of existing systems) or prediction data (for assessing policy impacts). They are not unique to either the trip based approach or the activity-based approach, but the two approaches can give different indicator scores in the case of assessing policy impacts, because they have different simulation models which give different predictions. The activity-based approach, however, offers another way to measure environmental noises and emissions. Since the approach provides detail records on where individuals spend their daily time, the time they stay in the places where are vulnerable to traffic noise and emissions can be used as an indicator to measure the extent to which people suffer from environmental consequences of traffic.

Social acceptability indicators assess the distributional effects of user benefits and environmental costs. Distributional effects are normally valued by equity indicators, e.g., Gini coefficient, standard deviation and Theil’s entropy index, etc. (Gaille, 1977 and Mulligan, 1991). The differences existing between the two approaches lay in the ways of how to represent user benefits and environmental costs. In the case of trip-based approach, what compared are the travel costs and benefits, while in the case of activity-based, the costs and benefits to participate activities are compared.

Economic viability assesses the investment and operating costs associated with the construction and operation of transport services, from the supply’s point of view. It is very difficult to estimate the capital costs and operating costs for the whole transport
system. However, it is normally part of the game in project appraisal or policy
evaluation to estimate the fixed and variable costs for implementing a policy or plan.
Therefore, the economic viability criterion is more relevant in evaluating proposed
plans or policies than assessing the whole transport system. The indicators can be
considered in this case, include the total capital costs required and expected annual
operating costs, etc.

3.4 Aggregation and Combination

There are various levels of urban transportation planning. These levels are different
from one to another in terms of planning contents and information requirements.
Sustainability analysis should be able to supply the information needs of different
planning levels. Table 2 summarizes some important aspects which characterize the
various levels of planning and presents what should sustainability analysis contribute
at each of levels. By aggregation and combination, sustainability indicators from
different perspectives can be manipulated to fulfill the information requirements of
different planning levels. In general, we distinguish the following 5 perspectives
based on which sustainability indicators can be derived:

a. Link-based: link-based indicators include level of service, traffic volume, travel
time (or travel speed), environmental emissions, noise level and energy consumption,
etc. They are the basic indicators for calculating indicators of other aggregation levels.
For example, by aggregating environmental emissions of the links covered, the zone-
based environmental emissions can be calculated; based on the average travel time on
links, accessibility indicators for locations, or zones can be calculated.

Table 2: Sustainability Analysis at Various Levels of Urban Transportation
Planning

<table>
<thead>
<tr>
<th></th>
<th>CITYWIDE PLANNING</th>
<th>PROJECT PLANNING</th>
<th>DETAILED DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning contents</td>
<td>the analysis or design of alternative modal networks at the citywide level.</td>
<td>the analysis or design of system components at the individual route or link level.</td>
<td>design or implementation of roads and traffic management facilities; scheduling of transportation services.</td>
</tr>
<tr>
<td>Spatial and temporal units of information most required</td>
<td>zonal level; annually and daily traffic data.</td>
<td>street block level; daily traffic data by mode.</td>
<td>individual locations; hourly traffic data by link and mode.</td>
</tr>
<tr>
<td>Information provided by sustainability analysis</td>
<td>system- and zone-based indicators</td>
<td>zone- and mode based indicators</td>
<td>link and location-based indicators</td>
</tr>
</tbody>
</table>
b. Zone-based (spatial aggregation): traffic zone is the spatial unit normally used in urban transport planning. At this level, planners and policy makers concern how people in the zone perceive the transport services they are provided. Do they suffer very much from traffic flows in terms of environmental impacts? Additionally, information on the differences of transport services enjoyed by different social groups in the zone are also relevant. Therefore, the relevant indicators from the zonal perspective include indicators of accessibility, environmental emission, traffic noise and distributional effects. These indicators are mostly required by the citywide and project planning levels.

c. Mode-based (sector aggregation): mode-based indicators include number of trips (or trip-kilometers) by mode, travel speed by mode, accessibility by mode, environmental emissions and energy consumption by mode, etc. These indicators are relevant for trading off plans or policies between different modes at the citywide level.

d. System-based (spatial and sector aggregation): evaluation at the system level assesses sustainability by taking the urban transport system as a whole. Despite general information on the transport system, such as, number of trips by mode, time of day and person type, average trip length, and annual environmental emissions from transport activities, etc., are required, information on distributional effects are also important for balancing transport service among sectors from the citywide point of view, planners.

e. Project-based (combination): project-based indicators are different from other four perspectives. These indicators combine indicators of the five dimensions of sustainability at a certain aggregation level. They are relevant for comparing different policies or plans in terms of expected overall impacts.

4 MODEL REQUIREMENTS

There are many models which are necessary to be used in the whole procedure of sustainability analysis. However, in general, three types of models can be distinguished, these are network models, simulation models and evaluation models.

Network models create topological sound link-node structure, to provide a base for the whole procedure. Ideally, we need a network which is able to provide detailed information at both micro-and macro-levels, so that it can support analysis at both aggregate and disaggregate levels. It can only be successful if a very detailed base network is constructed and a mechanism of network generalization is provided. One way to solve this problem is to construct several layers, each layer corresponding to a particular type of roads, such as freeway, arterial, and access, etc. To account for the variations within a link, dynamic segmentation techniques are normally required.
dynamic segmentation is particularly useful for aggregating link-based indicators into zone-based indicators. The activity-based approach requires accurate estimation of travel time between locations, it is most desirable that the most detailed network can be used.

Evaluation models transform outputs from simulation models to scores of indicators. Examples in this category include models for calculating environmental emissions, traffic noise, energy consumption; and user benefit indicators (trip- and activity-based accessibility), etc. Combination models for integrating indicators of different dimensions into an integrated index are also included. The whole family of multi-criteria analysis can be used as combination models. In addition, spatial and sector aggregation models also belong to this category.

Simulation models are used to simulate trip generation, trip distribution, modal split and traffic assignment over network. They include aggregate models (the four-stage model system) and disaggregate models (discrete choice models), or trip-based and activity-based models. Detailed description of these methods refer to Meyer and Miller (1984), Hutchinson (1974), and Ettema, et al. (1995), among others.

5 DATA REQUIREMENTS

There are five categories of data which we consider necessary for sustainability analysis in general:

a. physical information on land use and transport system. For example, locations and their connectivity to transport system of major service facilities, shopping centers, working places, home places; road network; topographical and surface data of roads; capacity of links and intersections; frequency, time table and routes of public transport; etc.

b. performance of transport system: traffic volume, travel time and speed by modes, by time of day, by links and by intersections, etc.

c. travel diary data collected from transport survey, statistics or other means. Basically these are those data regarding people's activity and travel behavior. Depending on specific models, different types of data are required. Examples include transport mode used for commuting, daily travel costs, etc.

d. data for calibrating models and deriving indicators. These data include coefficients for calibrating trip distribution models, technical coefficients for calculating air emission, noise and energy consumption, etc. For example, in the case of estimating

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energy consumption, we need the data on energy consumption rates of different types of vehicles, types of roads and car speeds.

e. data on policies and plans. These data represent the extent of changes of policy variables. For example, a road renew policy will be represented by the changing capacity or travel speed on that road, etc.

Most of the data required are geo-referenced, they are linked either to links on the network or to locations of facilities.

The data required are almost the same for the trip-based approach and the activity-based approach. Nevertheless, there are some differences regarding detailed levels. For example, with the activity-based approach, the physical information on land use has also to include data on institutional time constraints of activity sites. In the case of diary data, one has to collect data not only on travel behaviour but also on multi-dimensional information (where, when, frequency, for how long, with whom, etc.) of activities.

6 THE INFORMATICS FRAMEWORK

6.1 decision nature of transport plan and policy making

The diversities of data and models required in the whole process demand a tool which has the capacities to handle issues regarding organization and management of large data base and models. In this regard, the informatics technology especially the Spatial Decision Support System (SDSS) approach has great potential.

The SDSS approach is justified also from the point of view of the decision nature in urban transportation planning and policy making. They are ill-structured decisions in the sense that uncertainties exist in defining objectives and identifying impacts of intervention options. Like any decision making activities in urban planning, decision making in urban transportation planning has the following characteristics, which justify its ill-structuredness:

- it has multiple objectives, which sometimes are conflicting each other. For example, reduce congestion reduce environmental damage improve transport service;

- it has various stake-holders (or interest groups), who have different perceptions over priorities of objectives and solutions. For example, transportation planners, land use planners, politicians, environmentalists and the public, etc.; and
• it has a wide range of potential solutions, which generate impacts that sometimes counteract each other. Examples of solutions include policies of demand-oriented, supply-oriented, technology and physical planning.

These characteristics result in the difficulties in fully or precisely defining decision problems, objectives and impacts of policy options. Researchers term these kinds of decision problems as semi- or ill-structured decision problems. We intend to state that many decision making issues may consist of well- and ill-structured components and can not be simply termed as well- or ill-structured. The well-structured components can be easily simulated by mathematical models and computer programs, while the ill-structured components cannot. The answers to ill-structured problems rely on decision maker or expert's expertise and judgement. This nature demonstrates the requirement of a computer system which has interactive feature. SDSS is designed to support such kinds of decision making by integrating database management systems with analytical models, graphical display and tabular reporting capabilities, and expert knowledge.

6.2 the informatics framework

The informatics framework is formulated according to the principles of designing a decision support system. From a technical point of view, a successful decision support system is an integrated system of various information technologies. It should be able to provide multiple functions ranging from data management to strategy formulating support, so that decision making of different complexities can be supported. Table 3 describes the relationships among all these aspects. On the other hand, the structure of a decision support system should be designed according to decision making procedures and principles of software engineering.

In the context of the above described principles, the informatics framework for sustainability analysis in urban transport planning is proposed to have a structure as described in figure 4. The framework consists of five modules, namely a database, a model base, a knowledge base, the system control module and the user interface. The system control module is the critical part of the framework. If we say the model base the hand and data base is the stomach of a human being, then the system control module is his brain, and user interface is his face. It is the system control module which organizes models and data to provide decision support functions. It basically has two tasks: first it is an intermediate between the system and users, e.g., it translates users’ requirements into model language, and translate model output into simple and meaningful information to users; secondly it facilitates communications between various modules of the systems.

Regarding the implementation of the framework, we propose to make the best use of existing software. Geographical Information Systems (GISs) have a lot of advantages in data capturing, storing, manipulating, and displaying. Many of commercial GISs
provide basic transportation models, such as network analysis, etc. They are termed as GIS-T systems. Notable examples in this regard include Transcad, Aro/Info, and Genamap, etc. These systems can be used as a platform based on which to develop the proposed informatics framework.

Table 3: Decision Problems, Knowledge Needed, Techniques Used and Functions to Be Provided

<table>
<thead>
<tr>
<th>DECISION PROBLEMS</th>
<th>KNOWLEDGE NEEDED</th>
<th>TECHNIQUES NEEDED</th>
<th>FUNCTION TO BE PROVIDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is happening</td>
<td>domain knowledge</td>
<td>Database management systems</td>
<td>Data viewing and editing</td>
</tr>
<tr>
<td>What will be if...</td>
<td>inferential knowledge</td>
<td>operational models</td>
<td>what...if... analysis</td>
</tr>
<tr>
<td>How to plan and make decision</td>
<td>tactic knowledge or 'rules of thumb'</td>
<td>expert system</td>
<td>If...then... for plan and policy making</td>
</tr>
<tr>
<td>What should be done given the problems and objectives</td>
<td>strategic knowledge to guide planners or policy makers as to what ideas, information and analysis will be relevant</td>
<td>expert system</td>
<td>strategy formulator</td>
</tr>
</tbody>
</table>

7 CONCLUSIONS

The discussions in this paper outline step by step the developed informatics framework for sustainability analysis in urban transportation planning. It concludes that the complexity of information required and generated, and the models and procedures employed demonstrates the requirements of assistance from informatics technology. The decision support system concept, which distinguishes itself from GIS by strong analytical capabilities, is a promising solution in this regard. It claims a powerful tool in assisting planners and policy makers, who are confronted with requirements of sustainability in making their transport development policies. Further researches are required to implement the proposed conceptual framework.
8 REFERENCES


