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A PROCESS OF KNOWLEDGE REPRESENTATION FOR DEVELOPING TRANSPORT MODELS

by

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Abstract: The main focus of this paper lies in presenting a structured process of knowledge representation which constitutes the main qualitative part of a powerful modelling methodology known as System Dynamics. System Dynamics can contribute to understanding better the relationships between elements of the transport system and their environment. It can also be applied to construct useful tools for testing alternative transport-related policies.

Introduction

Transportation systems are multi-dimensional in that they are multi-modal, multi-sectoral, multi-faceted, multi-problematic, multi-purpose, multi-operational, multi-organisational, multi-effect, multi-ownership, multi-network, multi-technological and multi-disciplinary. In complex, large-scale systems, like transport, problems are rooted in the basic structure of the system. Actions taken to deal with one problem may create difficulties elsewhere.

A system is a number of components integrated into a complex entity, and system analysis simply means the consideration of the entity, rather than the separate consideration of individual components.

The systems approach can be defined as an organised, efficient procedure for representing, analysing and planning complex systems. It is a comprehensive, problem-solving methodology that involves two main steps:

1. the rational and creative structuring of both quantitative and qualitative knowledge, mainly in the form of models, to represent problems; and
2. the development of analytical techniques through which the problem can be analysed and solved.

System analysis is needed in order to treat problems in a comprehensive manner. System Dynamics, a member of the family of systems approaches, provides a systematic framework for modelling and understanding a number of systems and problems e.g. transport issues. Through using System Dynamics, attempts could be made to manage and control complex systems, like transport, in a better way and hopefully present plausible solutions to a lot of transport problems.

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System Dynamics

System Dynamics, originally called Industrial Dynamics, was developed at the Massachusetts Institute of Technology (MIT) during the sixties [1]. It is a powerful methodology that derives its roots from system theory, cybernetics, information science, organisational theory, feedback control theory, military games, and tactical decision-making. The main function of System Dynamics is to develop models of complex systems, and to experiment with them on digital computers.

System Dynamics pioneered the use of system concepts and computer simulation for the analysis of complex problems in business and management. It is a methodology of wide applicability that has become an appealing modelling style used by many different disciplines. Applications of System Dynamics cover a wide spectrum of different fields, disciplines and subjects. These include applications in defence, urban and regional development, business, banking, industry, agriculture, economics, finance, manufacturing, biology, education, health, medicine, dentistry, engineering, forestry, fishery, energy, environment, transportation, psychology, and various others.

From its name it can be inferred that System Dynamics is a methodology designed to help in understanding the dynamics of different real world systems. System Dynamics is based on control theory, sometimes referred to as the concept of servomechanisms. This presents a procedure to investigate and understand a system that is in the form of causal feedback relations. This feedback control procedure attempts to adjust the actual state of a system in order to achieve a desired state. These changes are brought about by decisions to implement control actions, which are attempting to narrow and close discrepancies, whether positive or negative, that exist between desired and actual conditions of the system (see Figure 1 [2]).

Adapted from [3], System Dynamics is defined as a rigorous method for qualitative description, exploration, and analysis, of complex systems in terms of their processes, information flows, organisational structure, delays, policies, decision rules and strategies. It facilitates quantitative analysis of systems, in terms of their behaviours, through computer simulation. System Dynamics provides a framework for the testing of policies, and the management of systems to achieve improved system behaviour.

Structural Components of a System Dynamics Model

System Dynamics models consist of time differential equations, of which there are basically three types; rates, levels and auxiliaries (see Figure 2). Rates represent the physical or information flows in a system (material, orders, money, people, equipment, etc). Basically, rates exemplify streams of policies, actions, strategies, decisions or activities that cause the state of the system to change. Levels represent the current state or condition of a system. A level is basically equal to the value of the same level at the previous point in time plus the net inflow/outflow of rates across the time increment. From a calculus point of view, levels are considered to be integrations of rates, while rates are time derivative of levels. Auxiliaries represent the algebraic or integral calculations that are mainly required to capture information necessary for the computation of rates. Thus auxiliaries simplify the computation of complex rates by algebraically splitting the computation of rates into several mathematical steps that are convenient to grasp, understand, formulate and present.

Most variables of System Dynamics models occur in feedback relationships and are thus endogenous (that is, determined within the model itself). Relatively few variables are specified exogenously by the model user (that is, influence the system but are not influenced by it). In System Dynamics modelling, the behaviour of a system is mainly determined by its structure. However, exogenous variables generated independently are also important to show how the endogenous structure of a system reacts to externalities.

The distinction between flows of real physical/material quantities, and flows of information should be clear. Physical flows are conserved flows that comply with physical rules. Information flows comply with their own particular laws.

In System Dynamics, time lags are explicitly taken into account. A lag in time is defined as the delay in time between the starting of an action and the ending of this action. There are two types of time delays, namely information and physical.

Variable Generation and Model Mapping

Models are finite entities and it is implied that in all modelling approaches some variables are to be included and others are to be excluded. It is not easy to select which variables to include in a model. What is more difficult is to decide which variables to include as exogenous to the model. Such inclusion and exclusion of variables depend mainly on the mental perception of the modeller to the defined problem. Whilst at the end of the day the modeller is responsible for which variables are included and/or excluded, there are sources of information and knowledge acquisition procedures that he/she may use to help identify and select variables, and construct and develop the functional relations of a System Dynamics model.

Sources of information

The following is a list of some of the sources of information and procedures that modellers can use in structuring their models.

1. Personal observations and direct individual experience of the modellers.
2. Literature search and content analysis.
3. Descriptive and formal (theoretical) knowledge.
4. Other existing models, facts, evidences, accepted theories, assumptions and hypothesis.
5. Existing Data (making use of statistical calibration and empirical estimation techniques).
6. Heuristics, intuitions, visions and inventions of actors as well as of modellers involved with a system.
7. Deterministic and/or stochastic specifications.

Knowledge acquisition

There exist two levels of knowledge elicitation. The first is the individual level which includes the following methods.

1. Clinical interviews with individuals to get an insight of their perceptions, beliefs, thoughts, views, values and impressions. Interviews can be structured or open ended i.e. unstructured interviews.
2. Nominal and judgmental questionnaires. These include choice, ranking and rating questions used to determine individual choices, preferences and attitudes. Examples of these are the revealed preference, the stated preference and the attitudinal survey questionnaires.

The second level of extracting knowledge and information is the group level. This involves eliciting knowledge and soliciting information from experts. This can take the form of expert opinions, mental concepts, consensus, practices and experiences. The following is a list of some of these techniques.

1. Cognitive techniques such as Delphi, see [4].
2. Brain storming.
3. Group meetings.
4. Discussions.
5. Structured workshops.

These techniques for extracting and capturing knowledge are well established in psychology and social sciences literature, as well as in behavioural and system structure studies. A relatively recent development in this field is the introduction and development of computer software like STELLA and computer based expert systems that are designed to help in the process of acquiring knowledge and information about a particular problem or system.

The System Dynamics modelling procedure acts as a filter through which the above sources of information could be synthesised. Synthesisation namely entails the explicit expression, organisation, structural mapping, and transfer, of available information to a set of quantitative relationships.

Steps Followed in Building a System Dynamics Model

The process of constructing a System Dynamics model induces an understanding about a modelled system as well as about the available policy options and their anticipated impacts on the behaviour of the system. The procedure involved in building a System Dynamics model is displayed in Figure 3. It comprises two levels of modelling. The first is the qualitative modelling which involves the identification and definition of a problem, and the verbalisation and conceptualisation of models. The second is the quantitative modelling which involves the formulation and programming of models and finally using the model for simulation and system analysis. The following presents a discussion of each of these steps in some detail.

Identification of a problem

Once gaps in the progress of any scientific discipline are recognised, or practical difficulties and limitations are encountered in dealing with any real world systems, politicians, scientists or researchers could identify this as a problem area. The potential subject requires careful thought, and inspection prior to research efforts.

Definition of a problem

A model builder has to establish a clear definition of a problem in general terms. He/She has to identify what are the specific questions that the model is attempting to answer, and consequentially the objectives and purposes of the model. Another important aspect is to identify the users who are expected to apply the model. These are crucial steps that can often dictate the general characteristics, the context, and the dimension demarcation, of the model to be developed. They involve establishing the purpose, the scope, the boundary (the breadth), and the level of detail (depth), of the model.

System verbalisation

Verbalisation mainly involves the clear explanation and description in writing of the mental concepts that lie the foundation for developing a model of a particular system. Verbalisation entails stating explicitly all the relevant information and knowledge on which the logic of the structural relations of the model is based. The variables and parameters that describe the system are identified and selected. This include choosing variable names, stating the directions of influences between variables, stating the types of influences, whether positive or negative, and explaining the rationale and hypothesis involved in formulating the model. The main advantage of the verbalisation step is that it acts as a communication media. This allows people to scrutinise and understand the model, and to gain a better insight and appreciation of the variables that are used in structuring the model relationships.

System conceptualisation

This involves developing a sound structural representation of a system in the form of causal and flow diagrams. These diagrams are intended to permit a more precise qualitative description and appreciation of the structural components of the system. It is appropriate at this point to assert the phrase "one diagram could be worth of a thousand words". Diagrams illuminate the mental concepts and the verbal explanations about a system.

Causal diagrams: Causal diagrams, sometimes referred to as system maps or influence diagrams, are simply the representation of the verbal description of a model in a graphical form. These graphical portrayals use the concept of signed digraphs, showing the full names of variables linked together by arrows that demonstrate the directions of influences (dependencies) between the variables. The nature of the causal link could be described in terms of being either positive or negative. 'Positive causality between A and B could be defined as: A has a positive influence on B if A adds to B, or if a change in A results in a change in B in the same direction. Negative causality between A and B could be defined as: A has a negative effect on B if A subtracts from B, or if a change in A results in a change in B in the opposite direction' [5]. Delays, namely the existence of time lags between a cause and an effect, should be also identified and marked. The causal interrelations form feedback loops, thus exhibiting the feedback mechanisms that characterise the structure of a system. A feedback loop is identified when the linkage between variables starts at one point and goes on in a cyclic path ending at the same point, and passing through at least one level variable. The polarity of a loop is determined by multiplying the signs around the loop. If the outcome is negative the loop has a negative net effect, whilst if the outcome is positive the loop has a positive net effect.

Flow diagrams: Using a set of specially devised System Dynamics diagram conventions, the causal diagrams can be transferred from the signed digraph form into flow diagrams. These System Dynamics conventions distinctly identify rates, levels, auxiliaries, constants, delays and exogenous variables (see Figure 2). The type of connections between variables, whether an information or a physical flow, are distinguished. As a result the system variables and the feedback loops are classified in a manner that allows easy and quick computer programming and simulation.

To demonstrate the steps of system conceptualisation, a few examples are shown in Figures 4, 5, 6 and 7. Figures 4 and 5 are mainly concerned with presenting the causal diagrams of construction and maintenance of roads [6]. Figure 6 shows the causal diagram of a bus transit system [7]. Figure 7 demonstrates the flow diagram of a model for passenger transport fuel demand in Australia [8].

It is obvious that System Dynamics modelling relies heavily on the diagrammatic representation of systems. If diagrams are well-designed and structured, formulating and developing System Dynamics models mathematically become relatively quick and easy. Diagrams are considered to be an essential step of the System Dynamics modelling procedure.

The main functions of diagrams are:

- to record the way in which a system works;
- to organise the mental and verbal models of a system in such a way that displays and explains the causality of components of a system;
- to identify the feedback loops of a system being modelled;
- to enhance communication, a medium through which mental soft models are filtered and translated into more consolidated notions; and
- to provide an inspiring educative medium, diagrams are helpful for thinking, overview, discussions, debate and documentation.

Model formulation

Building on the above steps, the mathematical formulations that represent the structural relations of a System Dynamics model are written. These provide the means to quantitatively examine the structure of a system. System Dynamics is used to model, understand and enhance the management of physical and social systems. While in social systems lots of relationships are highly qualitative in nature and difficult to represent quantitatively, most of the relationships describing physical systems can be quantitatively modelled. Sensitivity tests could play an important role in the formulation of System Dynamics models. The mathematical formulations of a System Dynamics model define the modelled system in terms of a set of simultaneous linear and non-linear differential equations.

Computer programming

Having carefully formulated the structure of a System Dynamics model, a computer language can be used to program the algebraic relations of the model, and code them into an executable computer program. The software is then debugged, and the logic of the programm verified. If DYNAMO or any similar computer language is chosen, the System Dynamics flow diagrams could be converted directly into a set of simultaneous differential equations. This substantially reduces the time and effort involved in the model formulation stage.

Simulation

The most difficult tasks facing system dynamicists lie mainly in the choice of appropriate parameters that describe a system, developing the structural relationships of the system, and designing and testing alternative policies. These tasks can be achieved through repeated simulation experiments. Simulation is intended to show the behaviour of the system in quantitative terms. The output of the simulation reflect the consequences of the structure used for formulating the model. Computer simulation runs show the most likely impacts of alternative policies on the state and performance of a system under study. Simulation serves this purpose in a relatively cheap, short, accurate and safe manner. System Dynamics simulation entails the numerical integration of the system differential equations over time.

System analysis

If the output of a simulation run shows inadequacies, namely something odd or wrong, the modeller asks why, looks for the answer by examining and assessing the structure of the model, modifies and develops what he/she thinks is necessary, tests the model by a new simulation run, and so on. This cyclic procedure of model inspection, interpretation, revision and simulation is one of the great strengths of the System Dynamics methodology. If the modeller follows this procedure, the model is improves greatly, and the modeller gains a thorough understanding of the system being modelled. Additionally, the output of models support decision-makers to improve their decisions regarding the choice of which policy to implement. The process involved in the development of a System Dynamics model should not be looked upon merely in terms of a final output, rather it should be perceived as a means for learning, accumulating knowledge, and performing qualitative and quantitative analysis about a system.

Stated in general terms, System Dynamics is a useful tool for:

- understanding and explaining the dynamic behaviour of a system in terms of its structure (causal relations and feedback loops) and policies, as well as improving the conceptual models that explain the system;
- the design, formulation, and testing, of different scenarios and policies by posing and answering the 'what if' type of questions;
- providing useful information, both, to policy- and decision-makers, thus giving support to the decision-making process in the field of strategic planning; and
- improving the management and control of complex systems. System Dynamics is a methodology through which powerful management tools are developed to enhance the abilities to control complex systems.

Conclusion

System Dynamics is a policy-orientated modelling technique that provides a framework for the design of policies, and the management of systems to achieve improved system behaviour. The process of actually constructing a System Dynamics model induces a substantial and extensive amount of intuition, understanding and learning about a modelled system, as well as about the available policy options and their anticipated impacts on the behaviour of the system. System Dynamics is a versatile and flexible modelling approach.

System Dynamics is designed to help in understanding the dynamics of different real world systems. In contrast to statism, dynamism could be referred to as the process of change in conditions of a system over time, namely the evolution of the behaviour of the system. In reality, many systems are adaptive, counter-intuitive and self-corrective. The most realistic way to represent the dynamic performance of such systems is for their behavioural dynamism to be induced as a result of the feedback causal structures that describe such systems. System Dynamics caters explicitly for the dynamic behaviour of systems. In general, dynamic modelling has been widely applied in other disciplines. In transport it is steadily gaining momentum in the midst of the conventional static planning approaches. This can be seen in the growth of interest in dynamic assignment models.

A very important function of the various modelling approaches is to use them to develop models (tools) that can act as credible supports to the policy and decision-making processes. Models that are carefully and diligently programmed act as intelligent amplifiers that stimulate creativity and filter the mental models of users. These models are not in any sense meant to replace decision-makers or even to inhibit their role in making decisions, rather they are developed to help and support them in achieving better decisions. The System Dynamics methodology can offer a lot in terms of better planning and solving transport related problems. System Dynamics should not be thought of as a methodology to replace or substitute for the traditional transport modelling approaches. Rather it should complement and be integrated with the existing approaches, to contribute, in a collective manner, to solving transport problems. In particular, System Dynamics is to be applied in strategic studies that are more concerned with policy analysis and decision-making in the field of transport.

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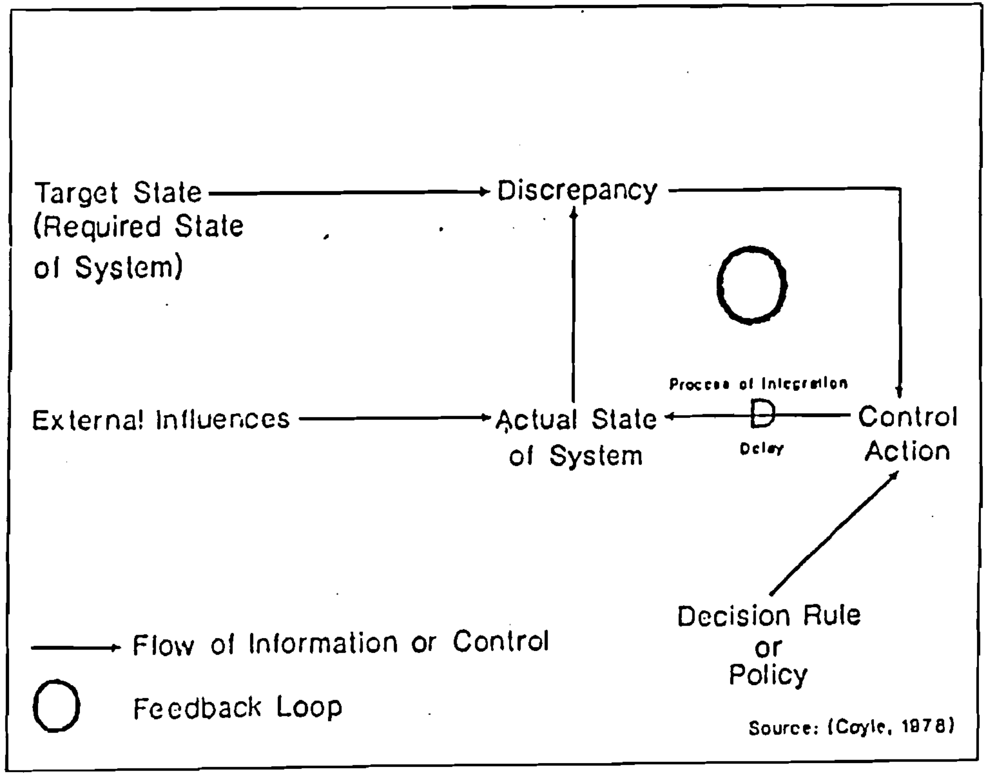


Source: (Coyle, 1978)

Figure 1 : Concept of control

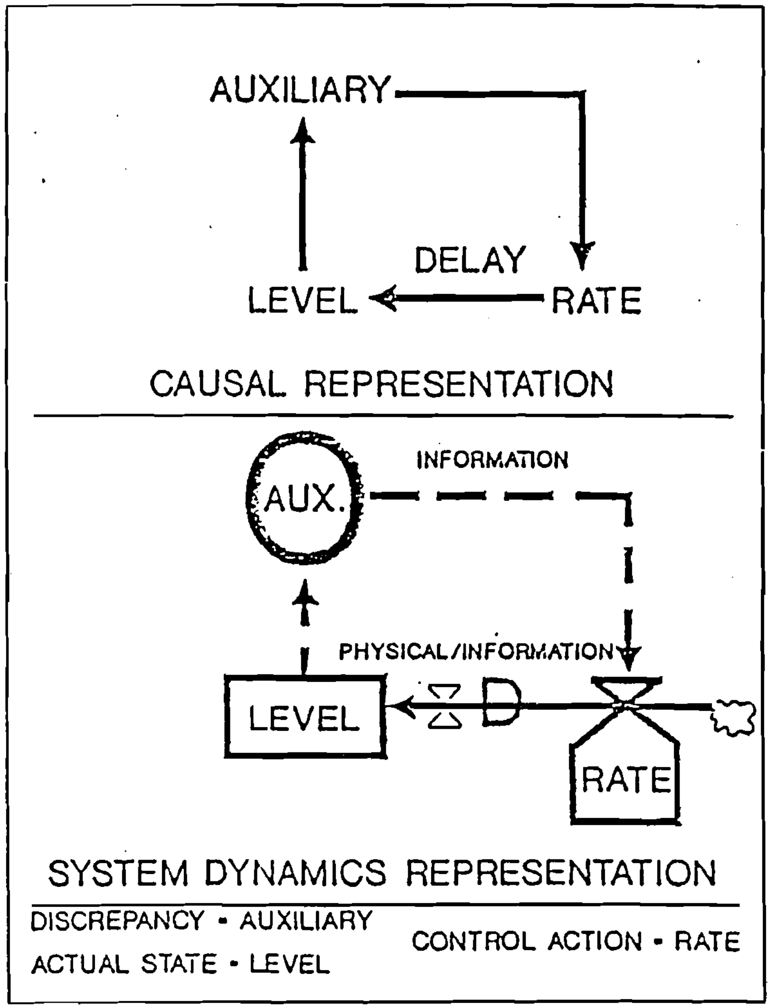


Figure 2 : Main types of variables used in System Dynamics modelling

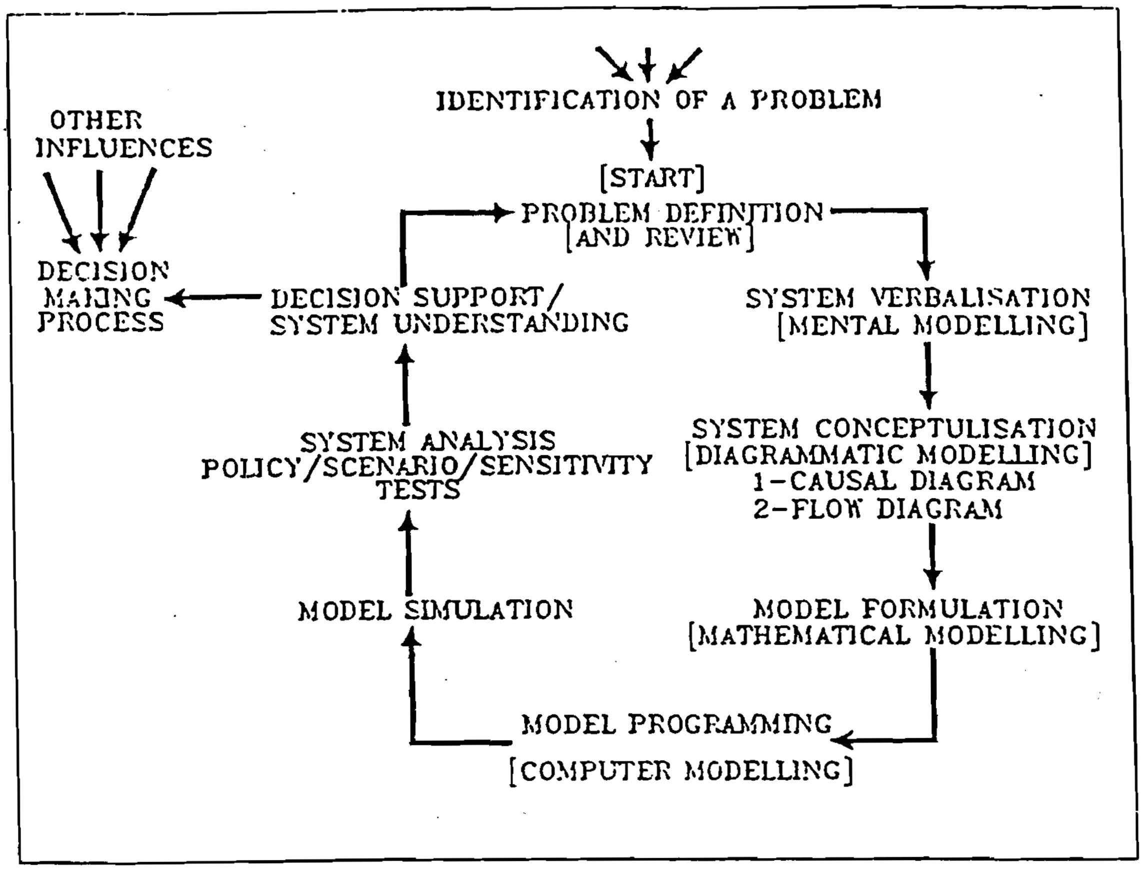


Figure 3 : Process of developing a System Dynamics model

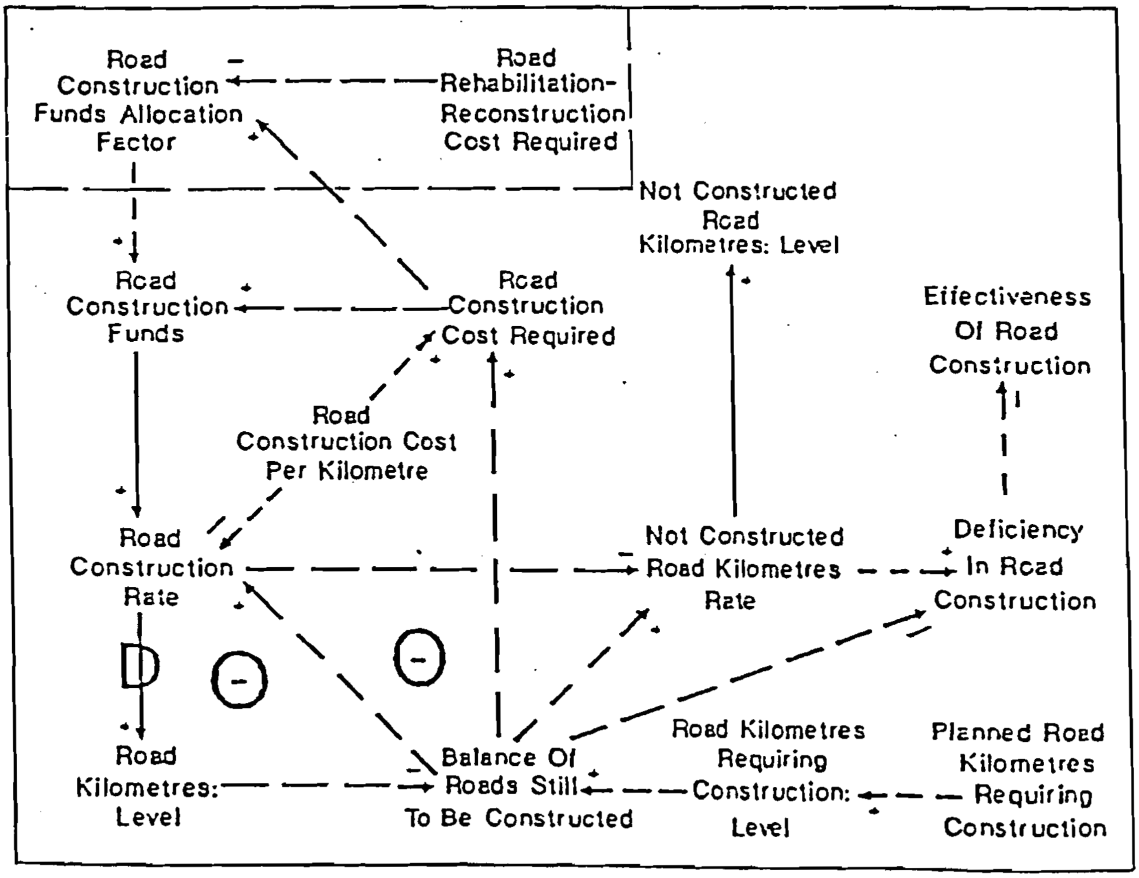


Figure 4 : Construction of roads

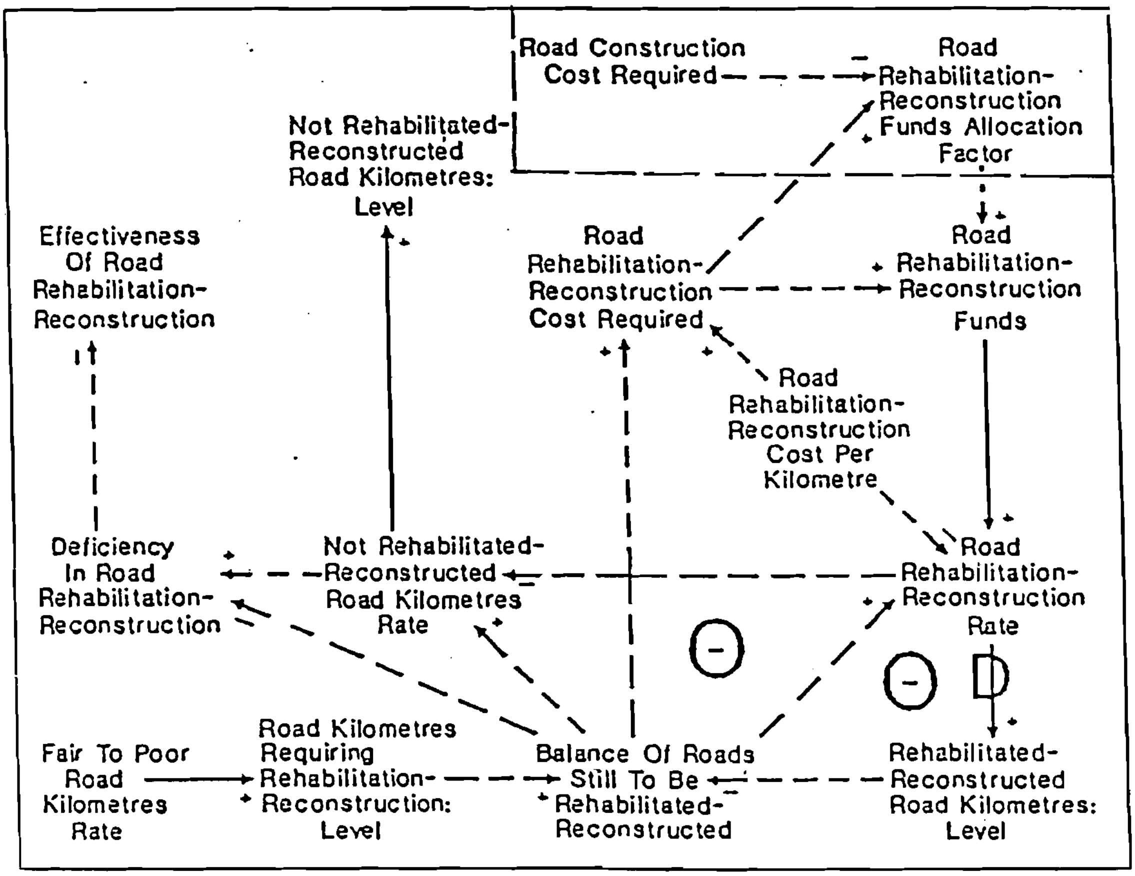
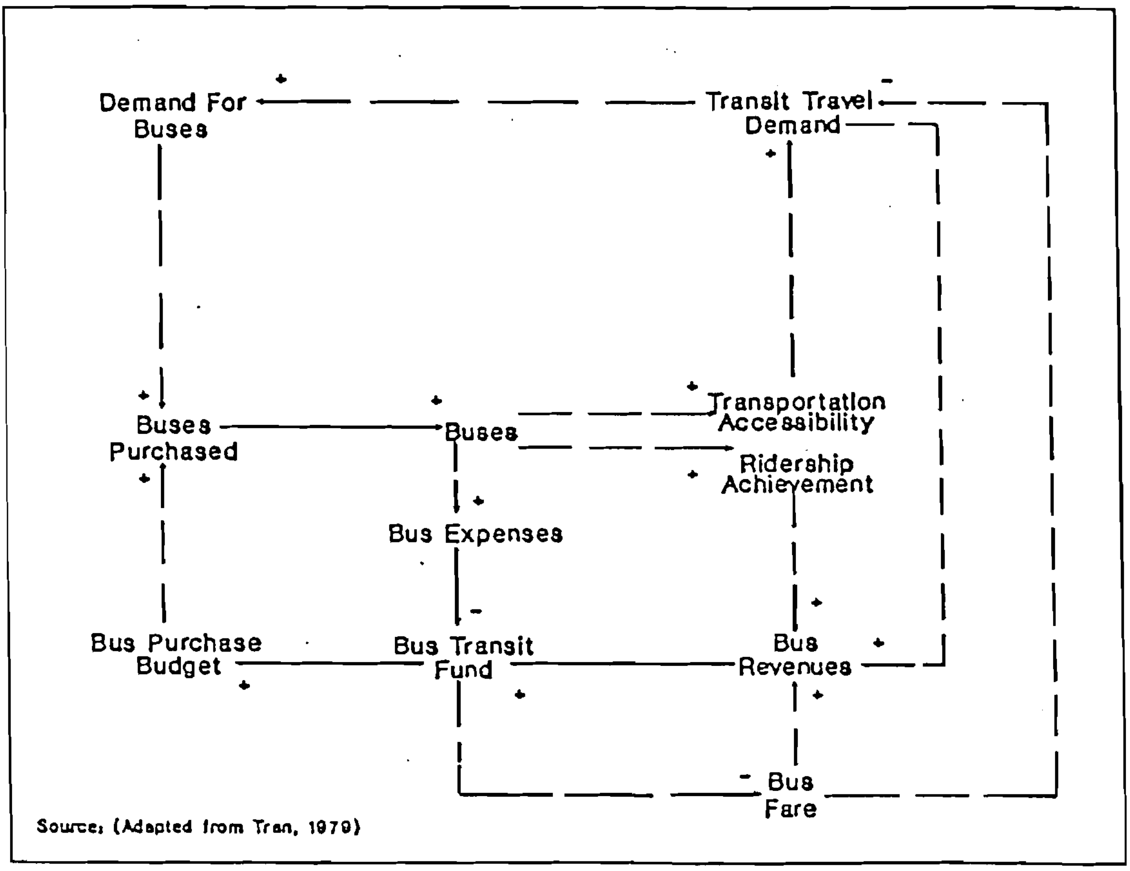
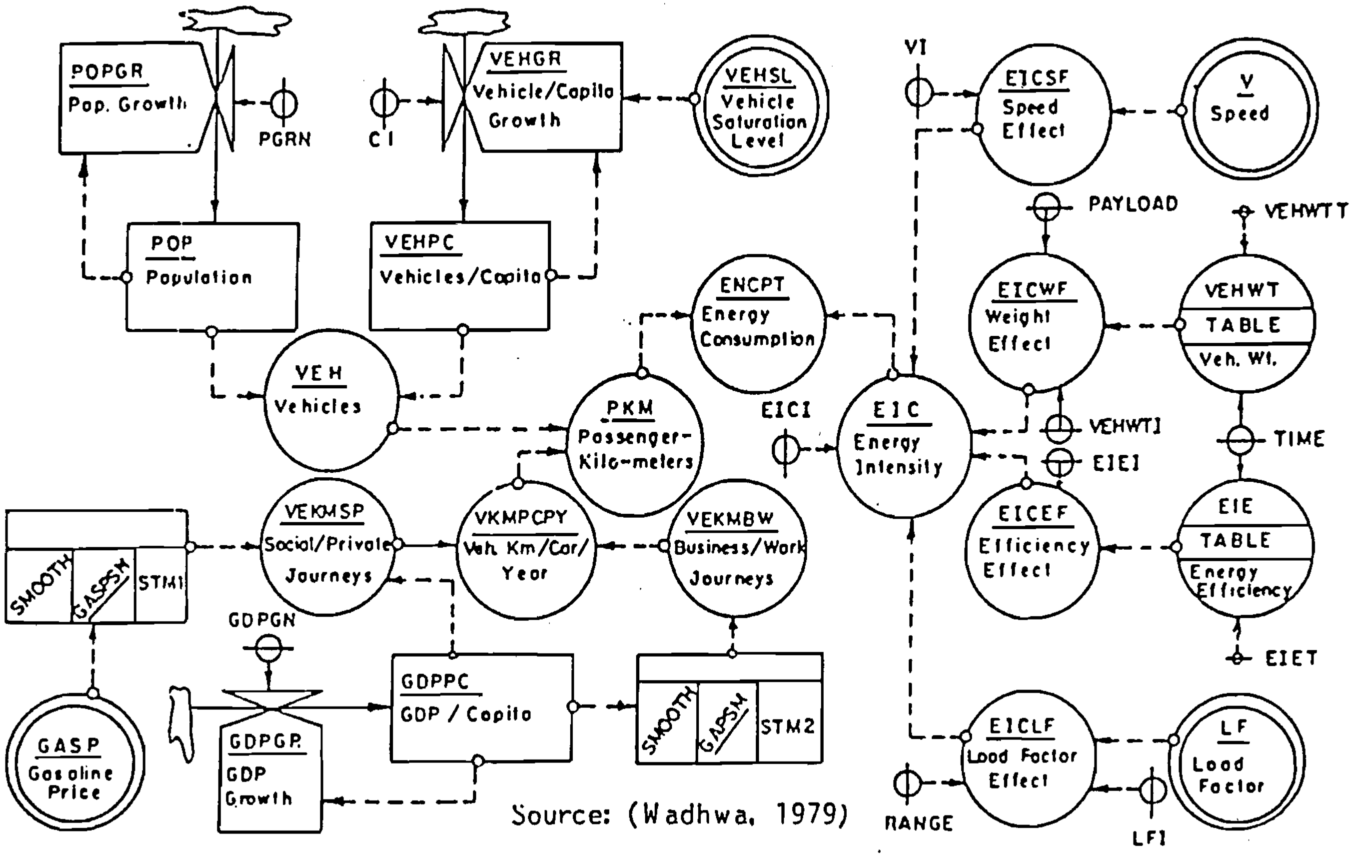


Figure 5 : Restoration of roads



Source: (Adapted from Tran, 1979)

Figure 6 : A bus transit system



Source: (Wadhwa, 1979)

Figure 7 : A passenger fuel demand system