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COMPUTER-BASED SUPPORT FOR THE MANAGEMENT OF INVESTMENTS IN ROAD INFRASTRUCTURE

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1. INTRODUCTION

Road transport is regarded as one of the key elements that contributes to the economic growth and development of a country. Lack or deterioration of roads represents a major obstacle to the prosperity and well-being of a country and investments in construction, maintenance and upgrading of roads constitute a large portion of their transport budget. The growing conflict between the requirements of the road network and the available financial resources is one of the most serious problems with which highway authorities have to deal.

There is a need for simplified planning techniques that are capable of testing alternative strategies for investing in the road network. These tools should provide powerful support to highway decision-makers so that they can make more rational and informed decisions. Decisions should be targeted towards achieving a better management and control of the road network system so as to maximise and sustain the benefits obtained from road investments.

Financial stringency requires the development of road management systems. These systems can be described as computerised, analytic tools that consider the whole-life costing of alternative strategies for the road network. These tools enable the testing of alternative planning programmes for the highway sector and hence the effective management of the road network.

2. PURPOSE AND APPROACH

The main purpose of this study is to construct a dynamic simulation model that describes the structural feedback interactions of the road network system. The model is meant to analyse the impacts of alternative road strategies. A road strategy involves the determination of; road funding levels, structure of the priorities involved in the allocation of road funds, and time intervention criteria for performing maintenance measures. This will lead to a more efficient management of the funds available for roads as well as to a more effective road maintenance programme.

The System Dynamics (SD) methodology is used in this study as the modelling framework within which the road management model is developed. The model simulates the effects of different road investment strategies. This is done by tracing the life-cycle costs of the activities which are necessary to develop and maintain the road system, and establishing the impacts that these activities have on the condition and performance of the road network.

The main objectives of the model are as listed below.

(1) To model the process involved in the allocation of road funds. This allocation process is meant to satisfy, (in a relative sense), the financial requirements of the changing physical condition of the road network. The two main constraints that are considered in this process of allocation include; the level of available funds and the priorities for allocating road funds to the main activities of the road network.
(2) To provide better insight and understanding of the dynamic, feedback nature of the road system.
(3) To act as an experimental management tool for assessing the short-term and long-term consequences of different road strategies on the physical development of the road system.
(4) To provide a common platform for estimating the main physical needs of the road system, the financial requirements and the effect of their provision on the condition/performance of the highway network. This will eventually assist in the management and control of the road system.
(5) To provide a set of performance indicators that describe the state of the road system at any point in its lifetime.

3. THE SYSTEMS APPROACH AND COMPUTER SIMULATION

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 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.

Computer simulation here refers to the use of a model to show the most likely impacts of various alternative policies on the state and performance of the system under study. Simulation serves this purpose in a relatively cheap, short, accurate and safe manner.

4. THE SYSTEM DYNAMICS METHODOLOGY

SD pioneered the use of system concepts and computer simulation for the analysis of complex problems in business and management. SD is a methodology of wide applicability. It has become an appealing modelling style used by many different disciplines. An extensive bibliographical list of the applications of SD to various transport issues is presented in Abbas, 1990c.

SD was developed at the Massachusetts Institute of Technology during the sixties (see Forrester, 1968). It is a powerful methodology based on feedback control theory which helps in understanding the dynamics of a system. SD models consist of time differential equations of which there are basically three types; rates, levels and auxiliaries. Rates represent the physical or informational flows in the system e.g. material, orders, money, people, equipment, etc. Levels are accumulations of the net inflow and outflow of rates over time. Auxiliaries represent the algebraic or integral calculations that are mainly required to capture information necessary for the computation of rates.

Computer simulation models based on SD provide a controlled experimental environment. The results from the models are arrived at through an informational feedback framework. Variables are linked in closed chains of causal relationships forming feedback loops. The models are made up of many such loops linked together. There are two basic types of feedback loop, positive and negative. Positive feedback loops generate amplified growth or decline i.e. they feedback upon themselves. Negative feedback loops generate goal seeking growth or decline i.e. they feedback towards achieving a stable target.

The procedure involved in building a SD model is represented in Figure 1. It is obvious from the diagram that SD modelling relies heavily on representing the system diagrammatically. If diagrams are well-designed, developing the model mathematically is relatively easy. It is to be noted that SD simulation entails the numerical integration, over time, of the system differential equations.

SD is a useful tool for:

- understanding and improving the management and control of complex systems;
- the design, formulation and evaluation of different scenarios by posing and answering the 'what if' type of question; and,
- providing useful information, both to the policy- and decision-makers, thus giving support to the decision-making process in the field of strategic planning.

The road provision model consists of two main parts, as shown in Figure 2. The first, is the user interface module, the second is the SD road provision model. The user interface module provides a flexible, easy-to-use medium to support the user in entering the exogenous parameters and specifications required by the model. SD facilitates the development of relatively uncomplicated road investment and maintenance models. A detailed description of the structure of the road provision model is given in Abbas, 1990a and 1990b.

5. MANAGING THE PROCESS OF ALLOCATION OF ROAD FUNDS

In each time interval of the simulation, road funds are allocated among five road system activities. Referring to Figure 3, the main activities of the road provision model include:

(1) road administration activity;
(2) routine road maintenance activity;
(3) road construction activity;
(4) road rehabilitation-reconstruction, i.e. restoration activity; and,
(5) periodic road maintenance activity.

This investment allocation process is performed in a dynamic fashion so as to be relatively consistent with the competing priorities and the changing demands of the road network system. The priorities for the allocation of road funds are set by the modeller. In this paper, the priorities are as shown in Table 1.

Table 1: Priorities for Allocation of Road Funds

The Road Network Funds	Priority
Road Administration Funds	1
Routine Road Maintenance Funds	2
Road Construction Funds	3
Road Restoration Funds	3
Periodic Road Maintenance Funds	5

Both construction and restoration of roads have the same priority regarding the allocation of road funds. This assumption is based on the fact that both construction and restoration of roads will eventually lead to kilometres of roads starting new life cycles. Absolute allocation is determined using allocation factors. These factors are computed according to the financial demand of the road construction activity versus that of the road restoration activity.

A main feature of the described allocation process is that the construction of roads takes priority over some of the maintenance measures. This is often the case with many road administrators/ politicians, as the construction of new roads is looked upon as a glamorous and prestigious activity to be appreciated by public opinion. The priorities given in Table 1 may be varied to permit the testing of different allocations of funds within the highway sector on the performance of the road network.

6. MAIN INPUT SPECIFICATIONS BY THE MODEL USER

The user interface module can be described as a computerised, friendly dialogue, designed mainly to foster creativity in constructing alternative scenarios for the road network, and also to work as a medium to facilitate the specification of the model's exogenous parameters by the user. It is also meant to act as a training tool for people unfamiliar with the road network system. The following presents the main input parameters of the model and describes the options available to represent these parameters, through using the user interface module.

- Initial unit costs of:

  (1) Yearly Road Administration Cost Per Kilometre.
  (2) Routine Road Maintenance Cost Per Kilometre.
  (3) Periodic Road Maintenance Cost Per Kilometre.
  (4) Road Construction Cost Per Kilometre.
  (5) Road Restoration Cost Per Kilometre.

- Inflation/deflation rates of the above stated unit costs.

- The user can choose from among several forms that are available for inputting road funds. Road Funds can be generated using any of the following options:

  (1) Empirical function. A non-linear polynomial function was chosen to represent the trend of road investment. This can be changed into any other linear or non-linear function that might represent local data in a better fashion.
  (2) Deterministic function.
  (3) Random Stochastic function (stochasticity is assumed to be of the Gaussian type, and randomness is based on the pseudo randomisation process). Repeated application of the stochastic function, in the manner of Monte Carlo simulation, would allow an analysis of the sensitivity with respect to the road funds.
  (4) Combination of any of the above, whereby at a time specified by the user, the function of the road funds changes from one form to another. Possible sequences offered in the program include:
  (a) Empirical function followed by deterministic function.
  (b) Empirical function followed by stochastic function.
  (c) Deterministic function followed by stochastic function.

  The flexibility provided in modelling the provision of road funds is meant to ease the process of changing the levels of road funds and studying their impacts on the condition/performance of the road network system. This type of sensitivity analysis can establish the optimum funding levels required to achieve a set of conditions for the road, as well as determining the funding levels that lead to the most economic return.

- The life cycle of a road progresses through time from an initial state of being in good condition, passing through a state of fair condition and terminating at a state of poor condition, where the road is almost unusable due to radical structure failure, i.e. high surface roughness values. The maintenance specifications of the model matches particular threshold criteria. These criteria can be described as warning times at which the condition of a road changes from one state to another and thus identify a need for intervention by performing a maintenance measure. The two main periods introduced to the model are defined below.

(1) Good Period, which represents the period of time the road lasts in a good condition, after which it requires periodic maintenance. Refer to Figures 4 (Harral 1988) and 5 (Bhandari 1988).

(2) Fair Period, which represents the period of time the road is in fair condition, after which it requires restoration. Refer to Figures 4 (Harral 1988) and 5 (Bhandari 1988).

As mentioned above, both threshold periods are meant to provide the times when the intervention criteria for performing periodic and restoration maintenance are satisfied. The user interface module provides several different forms for generating these intervention times at which the above-stated maintenance measures should be performed. These forms are described below.

(a) Deterministically scheduled to occur at a time specified by the model user. (*)

(b) Stochasticly scheduled to occur at a time specified by the model user. Time here is randomly generated, from a normal distribution, with a mean and a standard deviation specified by the model user. This option is introduced to cater for the relative uncertainty involved in determining the exact threshold times. (*)

(c) Condition responsive, according to the HDM III empirical, aggregate model (Paterson 1987), that describes the progression of roughness over paved roads. The HDM III equation is of the following form:

$$RI(t) = [RI_0 + 725[1+SNC]^{-4.99} NE_4(t)]e^{0.0153t}$$

where

$RI(t)$, RI_0	=	roughness at times t and t=0 respectively, in m/km IRI,
SNC	=	modified structural number,
t	=	age of the pavement since restoration or construction,

$NE_4(t)$ = cumulative equivalent standard axle (ESA) loadings until time t, using damage factor =4, in million ESA/lane.

It is to be noted that surface roughness of roads is considered to be the most representable performance indicator of the changing condition of paved roads over time. (**)

(*) Scheduled maintenance is made at a specific time in the life of a road. Scheduled maintenance, sometimes called preventive maintenance, is applied irrespective of the actual condition of the road at the time of maintenance. Scheduling of maintenance measures can be tested for periods of different durations.

(**) Condition responsive maintenance is performed at a time when the condition of the road has deteriorated to a prescribed threshold level. This conditional level is specified by the user according to his acceptable criteria regarding the performance of roads.

The options available for formulating the maintenance threshold criteria are meant to cover different practices involved in determining the intervention times for road maintenance. Existence of such flexibility leads to more rational road strategies being attained. These strategies can identify optimal points in time when particular types of maintenance measures are due.

- If due to lack of funds, periodic maintenance were not done on time, some of the model users might then like to consider different warranty times for performing periodic maintenance. Two options are available through the user interface module:
  (1) Periodic maintenance is still only warranted once the road condition changes from good to fair; and,
  (2) An extension to the warranty time for performing periodic maintenance is specified by the model user.

- The extent of betterment which we expect periodic maintenance to have on the road is a controversial matter. The user interface module provides the user with the flexibility of choosing from three expected impacts that periodic maintenance might have on the age/condition of the road. The three possibilities are:

  (1) No significant, noticeable or measurable effect;
  (2) Restarting a new life-cycle for the road; and,
  (3) Prolonging the life-cycle of the road. In this case the user has to specify the length of time by which the life-cycle is expected to be prolonged due to periodic maintenance.

- From the above, it is clear that in the course of the simulation, the road provision model assesses the condition/performance of roads and takes into consideration a set of maintenance options and standards. The type and frequency of applied maintenance measures can significantly affect the performance of roads. For each time increment in the analysis period, the model compares the simulated condition/performance of the road network with the specifications prescribed through the user interface module. Whenever a specification is attained a maintenance measure is rendered to be executed.

- It is worth noting that the options available through the user interface module allow the specification of the input parameters in different combinations of; deterministic, stochastic and empirical forms.

7. <u>MAIN ASSUMPTIONS AND DEFINITIONS OF THE MODEL</u>

This section is meant to explain the main implicit assumptions and definitions of the System Dynamics road provision model.

- Total Permitted Road Kilometres, is a parameter that explicitly caters for the constraint of land-use planning taking into account the following constants:

    - maximum land area of the region;
    - maximum allowed ratio of road area to land area; and
    - average road width.

  The constants are exogenously specified by the model user. On the other hand, it is to be noted that another System Dynamics model is currently under development which is expected to explicitly model the dynamics of the demand for road construction.

- Selection and scheduling of maintenance measures are mainly based on what has been stated by Harral, 1988, in a World Bank road policy study, i.e. that recent field surveys, supplemented by the judgement of engineers of the World Bank, suggest it is possible to distribute a country's roads among three classes of condition: good, fair, and poor. A road in good condition requires only routine maintenance to remain that way. A road in fair condition needs resurfacing, i.e. periodic maintenance. A road in poor condition has deteriorated to the point that it requires either partial or full reconstruction, i.e. restoration.

- Good To Fair Road Kilometres Rate, is the rate that dynamically determines the number of kilometres of roads which degrade from good to fair condition, over the incremental time intervals of the simulation. Periodic road maintenance of a road is considered necessary once the road condition degrades from good to fair. It is vital to perform the periodic maintenance on time. Periodic maintenance is supposed to better the existing condition of a road and to prolong its life-cycle. There are different views pertaining to the exact extent of this betterment, some of which have been treated in the previous section of the paper.

- Fair To Poor Road Kilometres Rate, is the rate that dynamically determines the number of kilometres of roads which degrade from fair to poor condition, over the incremental time intervals of the simulation. Restoration of a road is considered necessary once the road condition falls from fair to poor. Once restorated, the road kilometres restart a new life-cycle.

- Good-Fair Condition Road Kilometres: Level, represents the accumulation of road kilometres, which are in a good or fair condition, over time, and hence requiring annual routine maintenance.

- To avoid double counting, in performing the maintenance measures, Periodic Road Maintenance Rate is subtracted from the Routine Road Maintenance Rate. This avoids performing routine maintenance to road kilometres which are already expected to be periodically maintained.

- Evaluation of different road strategies is mainly carried out by comparing the output of the model, which is mainly in the form of performance indicators, against the user criteria. Many decisions concerning the road network system can be made on the basis of performance predictions. These include: state/performance, deficiencies and efficiencies, physical and financial requirements and expenditure details of the road network.

Economic evaluation is carried out based on comparing the present value of incurred costs of alternative road strategies. The model is structured to keep the input data to a minimum, yet to produce a comprehensive output of the condition of, and expenditure on the road network. This information enables the model user to rationalise decision making concerning road funding strategies and maintenance options. The procedure involved in the evaluation of the different road strategies is presented in Figure 6. Policies are selected according to their ability to produce a level of service that is acceptable by decision-makers.

8. SUMMARY AND CONCLUSIONS

A simulation model for the dynamic provision of roads is presented. The model simulates the effects of road investment policies on the development of the road network system where these investments are allocated among the construction, maintenance and administrative activities. The maintenance measures involved are routine, periodic and restoration maintenance. The model is a tool for analysing policy and is meant to give information about the structure and performance of the road network system. The road provision model allows us to analyse the life-cycle costs of a road under a variety of alternative road funding policies, maintenance options, initial unit costs, inflation and discount rates, etc.

According to Coyle, 1978, SD, the modelling approach used in this study, seems to fulfil a need, which is not met by the standard planning and programming approaches, namely that of providing for the concept of controllability. SD is a very strong, policy-orientated modelling technique.

In attempting to present the road provision model, three main topics were addressed: firstly, to indicate how available road funds would be allocated into major appropriation categories; secondly, to show the main input parameters required by the model and to explain the options available for inputting each parameter by using the flexible and simple user interface module; and thirdly, to introduce the main implicit assumptions and definitions of the structure of the model. The evaluation/ optimisation procedure introduced in this paper is heuristic in nature. Heuristic optimisation can help to familiarise transport personnel with the road network system, but over the long run it may become tedious because of the need to intervene manually on many occasions. The development of computerised optimisation algorithms would be a major step forward in the sophistication and ease of use of the model described in this paper.

The overall objective of the developed model is to serve as a management tool for designing, testing and assessing strategies that support the decision making process in the field of Highway planning. The model could be used by transportation system managers, in policy planning, and by government decision-makers in making better decisions concerning the road network system.

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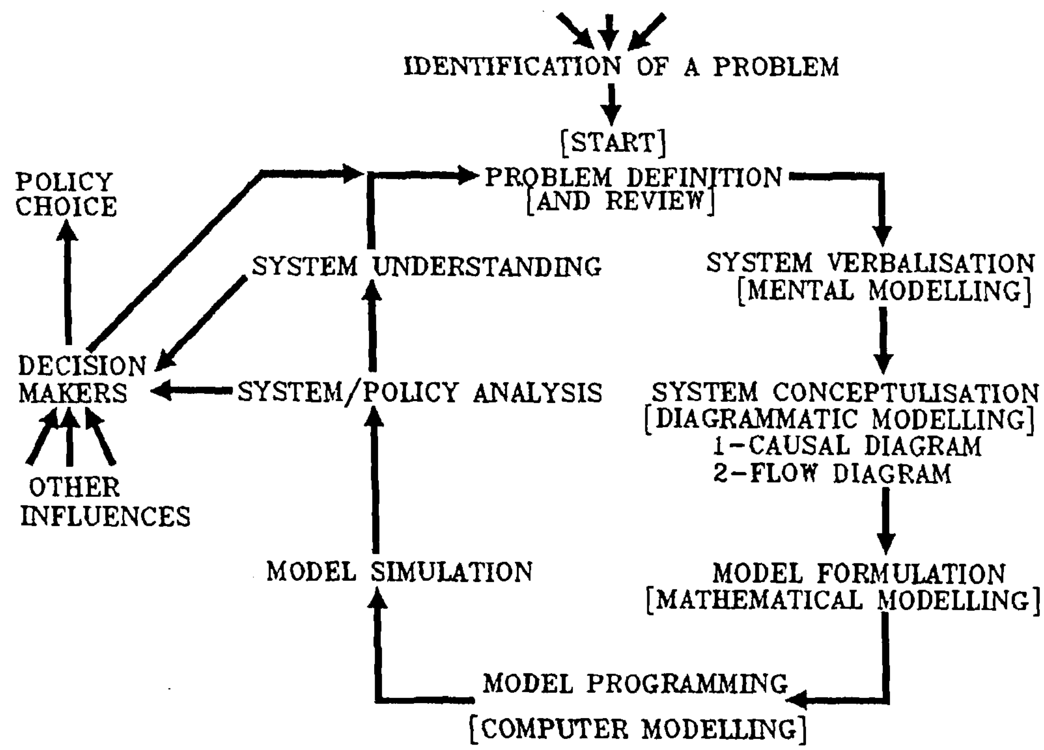

Fig. 1: Procedure Involved in Building a System Dynamics Model

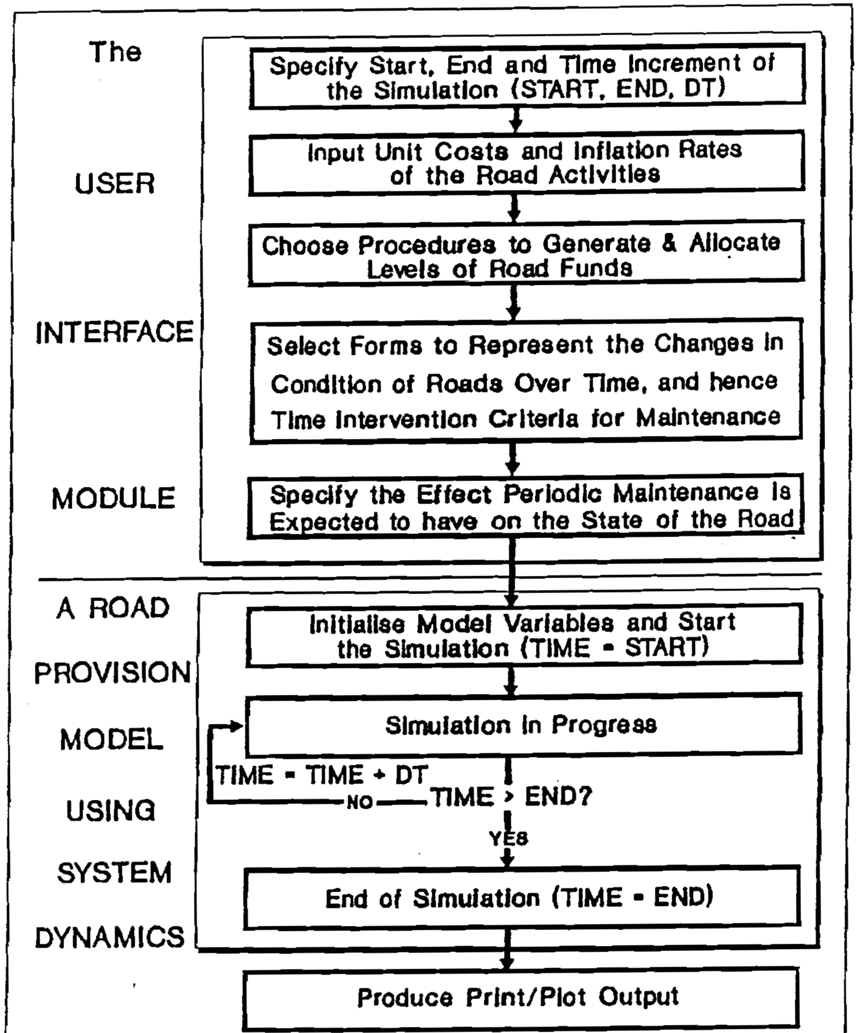

Fig. 2: Framework of the Road Provision Model

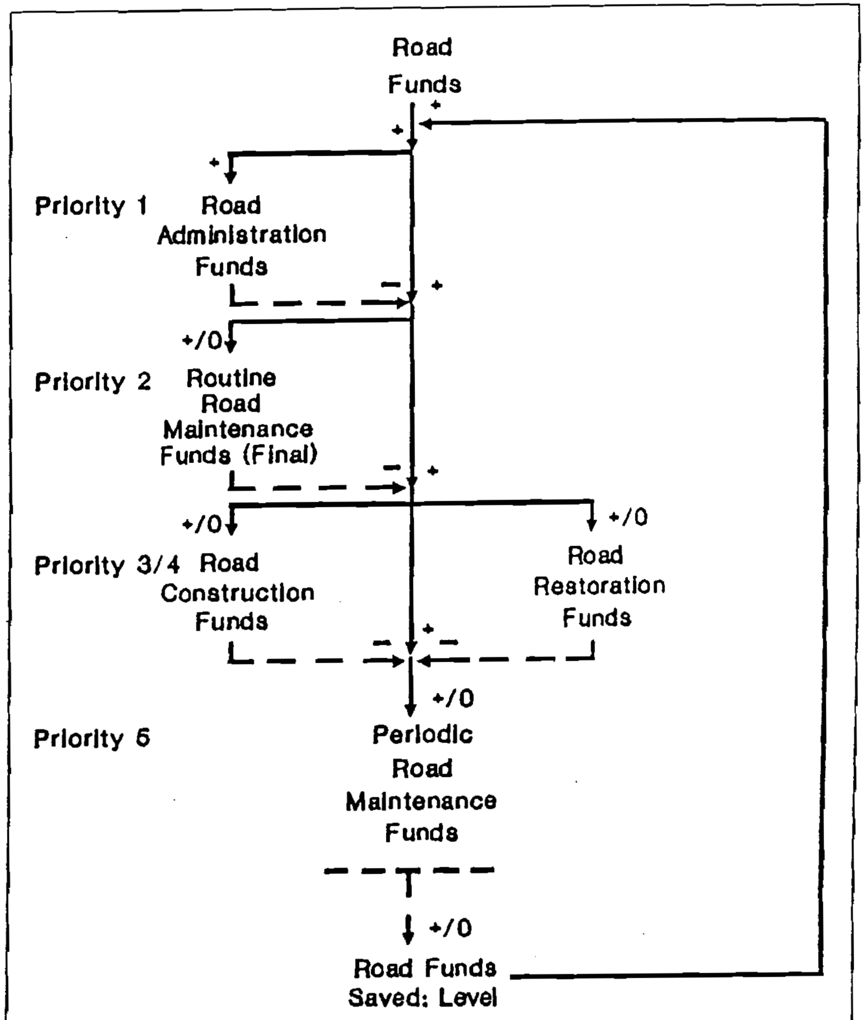

Fig. 3: Management of the Allocation of Road Funds

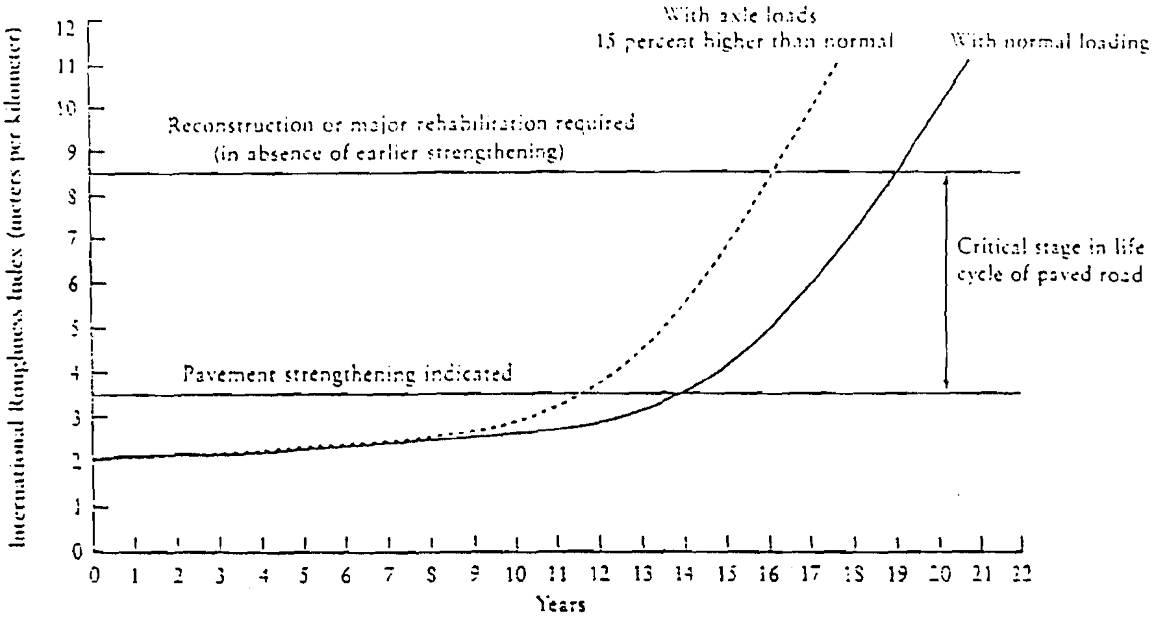

Fig. 4: Deterioration of Paved Roads Over Time (Source: Harrel 1988)

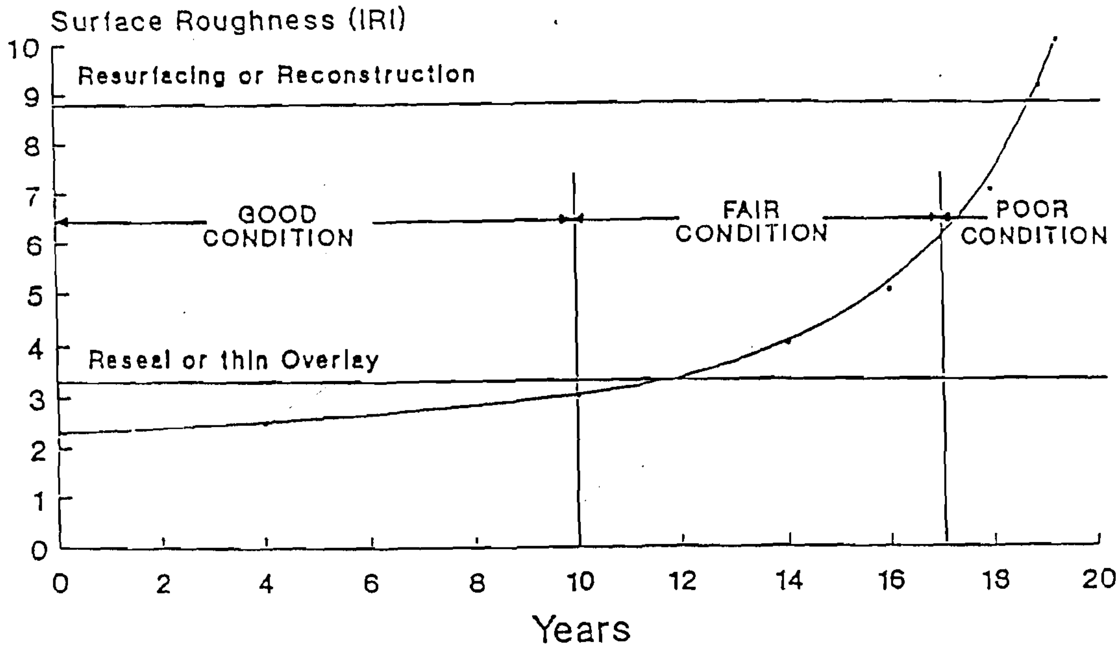

Fig. 5: Condition of Paved Roads Over Time (Source: Bhandari 1988)

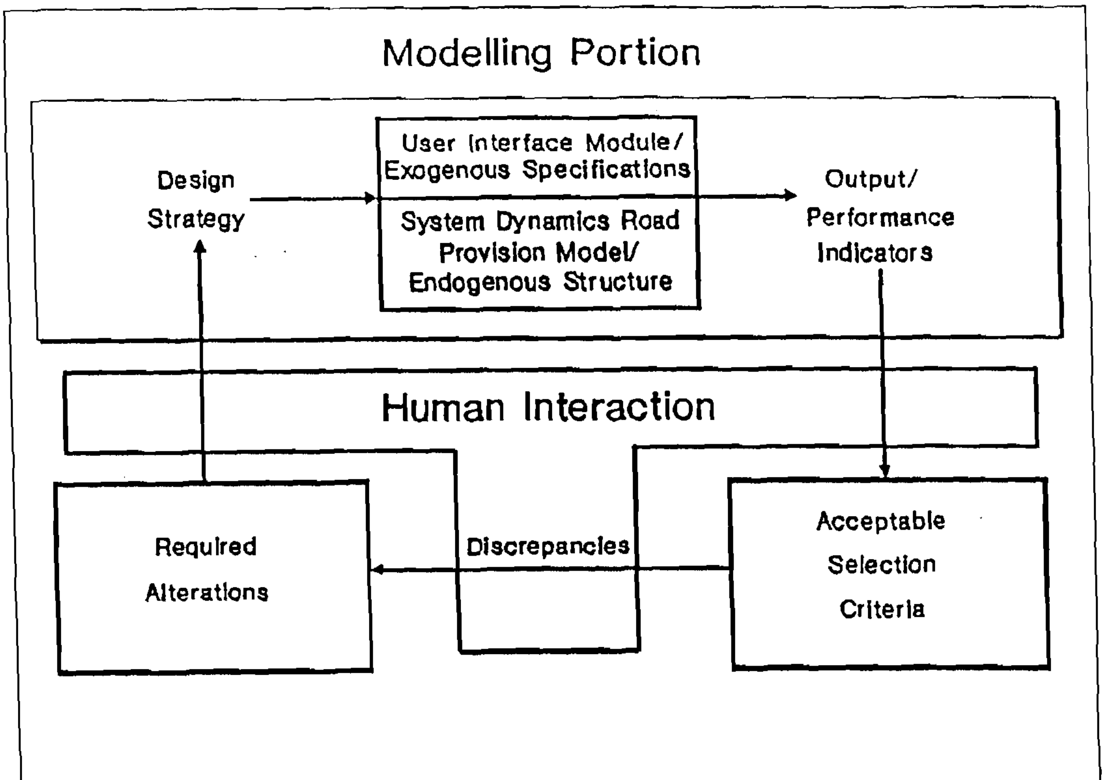

Fig. 6: Procedure Involved in Evaluating Road Strategies