A Road Provision Model Using System Dynamics

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ABSTRACT

One of the most difficult tasks facing highway administrators is how to efficiently manage the allocation of road funds. In this paper a comprehensible, easy-to-use, highway management tool is presented. This tool takes the form of a computer simulation model which is intended to assist managers of a network of highways to make better decisions concerning the allocation of scarce funds. It mainly simulates the effects of different investment strategies and maintenance options on the road network. This is done by tracing the life-cycle costs of the major activities of providing and maintaining the road system, and by considering the effects that these activities have on the state and performance of the road network.

1. INTRODUCTION

The continued development of the road network is looked upon as a necessity that contributes to the prosperity and wellbeing of a country. Construction, maintenance and upgrading of roads constitute a large portion of the transport budget in many countries, yet the growing conflict between the requirements of the road network and the available financial resources is one of the most serious problems that highway authorities have to deal with. There is a need for simplified planning techniques that are capable of testing alternative strategies for investing in the road network system.

This financial stringency requires the development of road management systems to provide support for highway decision-makers so that they can make more rational, informed decisions. These decisions should be targeted towards achieving a better management and control of the road network system.

Road management 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 management and planning programmes for the highway sector.

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 proposed changes in the funding levels, as well as in the structure of the priorities involved in the allocation of road funds.

The System Dynamics methodology, (Forrester 1968), 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- and long-term consequences of different road strategies on the physical development of the road system. A road strategy involves the determination of; road funding levels, priorities for allocating road funds and time intervention criteria for performing maintenance activities.
(4) To assist in 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. MODEL DESCRIPTION

The road provision model consists of two main parts, as shown in Figure 1. The first, is the user interface module, the second is the System Dynamics road provision module, see (Abbas 1990).

In this section, the System Dynamics conceptual model is introduced. The feedback interaction between demand and supply of the road network system is explicitly considered. The main assumptions and some of the important variables of the model are explained. Causal diagrams are considered to be an advanced and comprehensible step of the System Dynamics modelling procedure. This paper presents the fundamental, causal mechanisms underlying the structure of the System Dynamics road provision model.

3.1 Managing the Process of Allocation of Road Funds

Each time interval of the simulation, road funds are allocated among five road system activities. Referring to Figure 2 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 to be in accordance with the most commonly practised management of road funds in developing regions. 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 Rehabilitation-Reconstruction 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 activiy versus that of the road restoration activity.

The stated structure, describing the priorities, considered in the allocation of road funds may be varied to test the effects on road network performance of alternative priorities for the allocation of road funds.

3.2 Main Assumptions and Definitions of the Model

In this section of the paper, the reader is advised to refer to the causal diagrams describing the structure of the model and presented throughout Figures 2 to 9. This section is meant to explain the main implicit assumptions and definitions of the System Dynamics road provision model.

- Total Permitted Road Kilometres, (refer to Figure 5), 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 demand for road cosntruction.

- 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. (Harral 1988)

- Good To Fair Road Kilometres Rate, (refer to Figures 7 & 8), is the rate that dynamically determines the number of kilometres of roads degrading 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 certainly betters the existing condition of a road and prolongs its life-cycle. There are different views pertaining to the exact extent of this betterment, but discussion of these views is outside the scope of this paper.

- Fair To Poor Road Kilometres Rate, (refer to Figures 6 & 8), is the rate that dynamically determines the number of kilometres of roads degrading 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, (refer to Figures 4 & 8), represents the accumulation of road kilometres, which are in a good or fair condition, over time, and hence requiring annual routine maintenace.

- To avoid double counting in the maintenance activities, 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, (refer to Figure 4).

- 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. Some of the main road performance indicators produced by the model are listed below.

(1) Number of Kilometres of roads in:
  (a) good condition;
  (b) fair condition; and
  (c) poor condition.

(2) Efficiency and deficiency indices of:
  (a) administration of roads;
  (b) construction of roads;
  (c) routine maintenance of roads;

(d) restoration of roads; and
(e) periodic maintenance of roads.

(3) Expenditure and levels of:
(a) constructed roads;
(b) administered roads;
(c) routinely maintained roads;
(d) restorated roads; and
(e) periodically maintained roads.

3.3 Main Input Values by the Model User

The user interface module can be described as a computerised, friendly dialogue, designed mainly to instigate creativity in constructing alternative scenarios for the road network, and also to work as a medium to facilitate the specifiction of the model exogenous parameters by the user. 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 cost 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 Rehabilitation-Reconstruction Cost Per Kilometre. (Refer to Figure 10)

- Inflation/deflation rates of the previously stated unit costs. (Refer to Figure 10)

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

(1) Empirical function (linear or nonlinear).
(2) Deterministic function.
(3) Random Stochastic function (stochasticity assumed to be of the Gaussian type, and randomness is based on the pseudo randomisation process).
(4) Combination of any of the above i.e. at a time specified by the user, the function of the road funds changes from one form to another. The available combinations include:
(a) Empirical function with Deterministic function.
(b) Empirical function with Stochastic function.
(c) Deterministic function with Stochastic function.

- 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 times at which the condition of a road changes from one state to another. The main two threshold times introduced to the model are defined below.

(1) Good To Fair Period, which represents the period of time the road lasts in a good condition i.e. the time when road condition changes from good to fair, and hence requires periodic maintenance. Refer to Figures 11 (Harral 1988) and 12 (Bhandari 1988)

(2) Fair To Poor Period, which represents the period of time over which a road life cycle lasts i.e. the time when road condition changes from fair to poor, and hence requires restoration. Refer to Figures 11 (Harral 1988) and 12 (Bhandari 1988)

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

(**) 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 model is structured to keep the input data to a minimum, yet to produce a comprehensive output of the condition and expenditure of the road network. This information enables a thorough examination by the model user, thus rationalising the decision making, concerning road funding strategies and maintenance combination options.

4. SUMMARY AND CONCLUSION

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. The investments are allocated among the construction, maintenance and administrative activities. The maintenance activities involved are routine, periodic and restoration maintenance. The model is a typical policy analysis tool 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 rates, etc.

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

In attempting to present the road provision model, three main topics were addressed. First, to indicate how available road funds would be allocated into major appropriation categories. Second, to introduce a set of uncomplicated, yet reasonably, comprehensive submodels of the road system. These submodels when linked together form the structure of the System Dynamics road provision module. Third, to show the main input parameters required by the model and to explain the options available for inputing each parameter by using the flexible user interface module.

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 is to 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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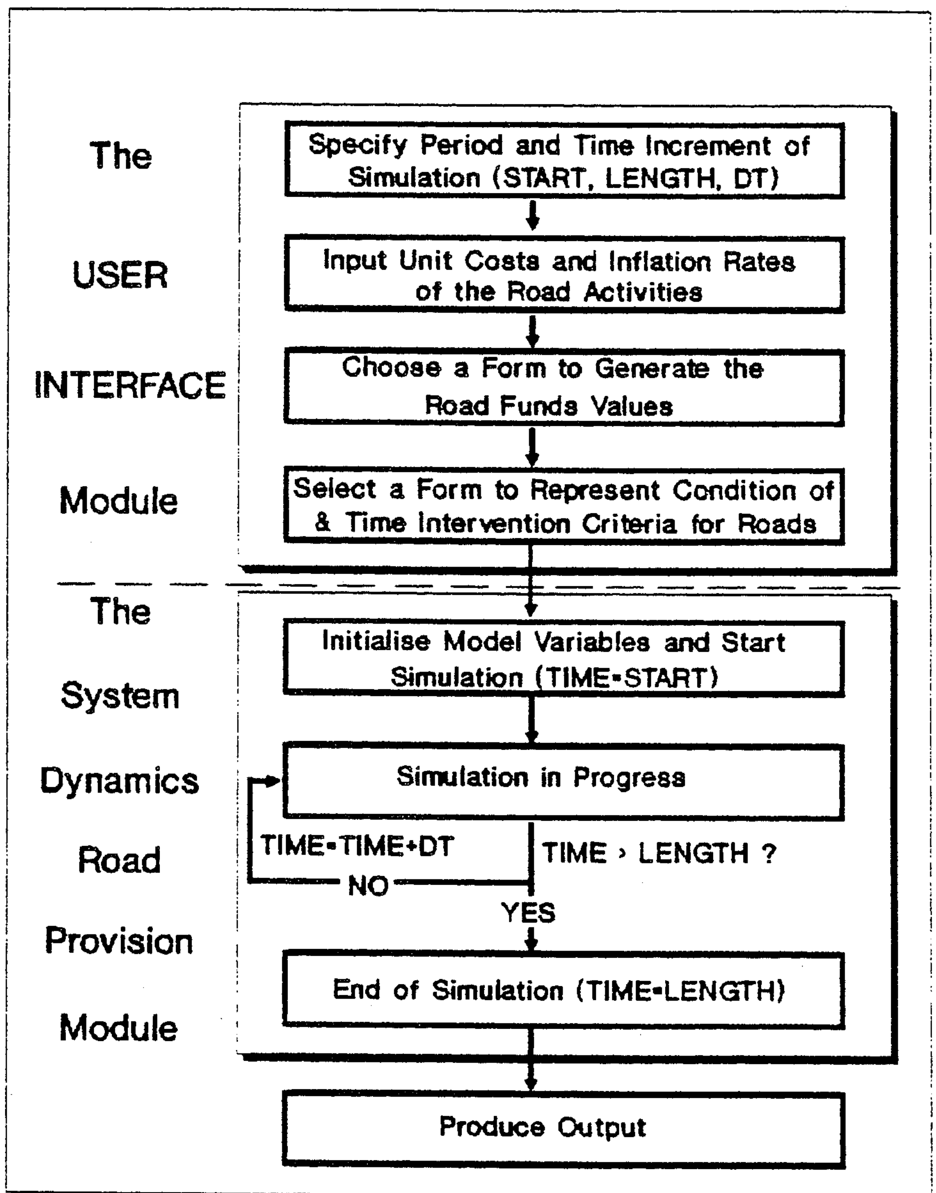

Fig 1: Framework of the Road Provision Model

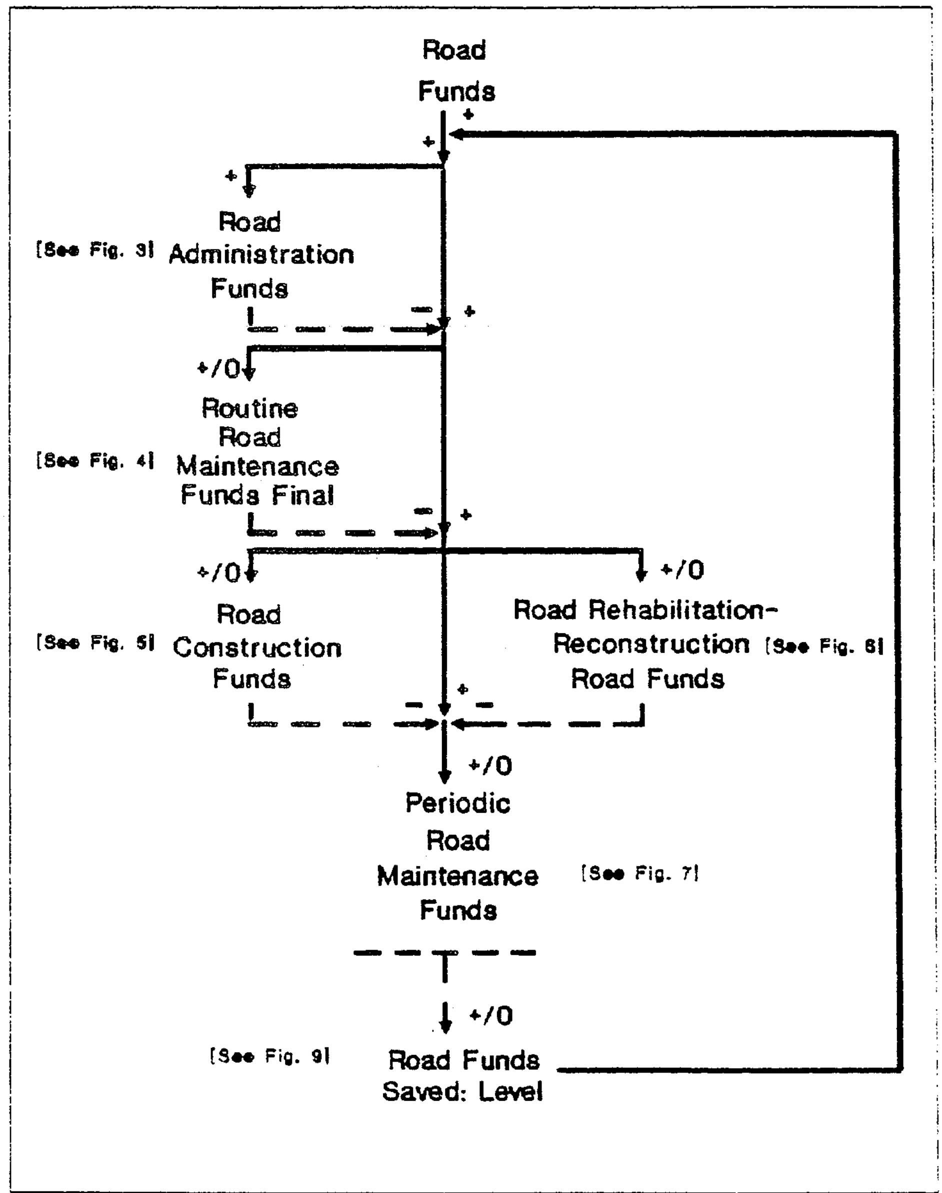

Fig 2: Management of the Road Funds

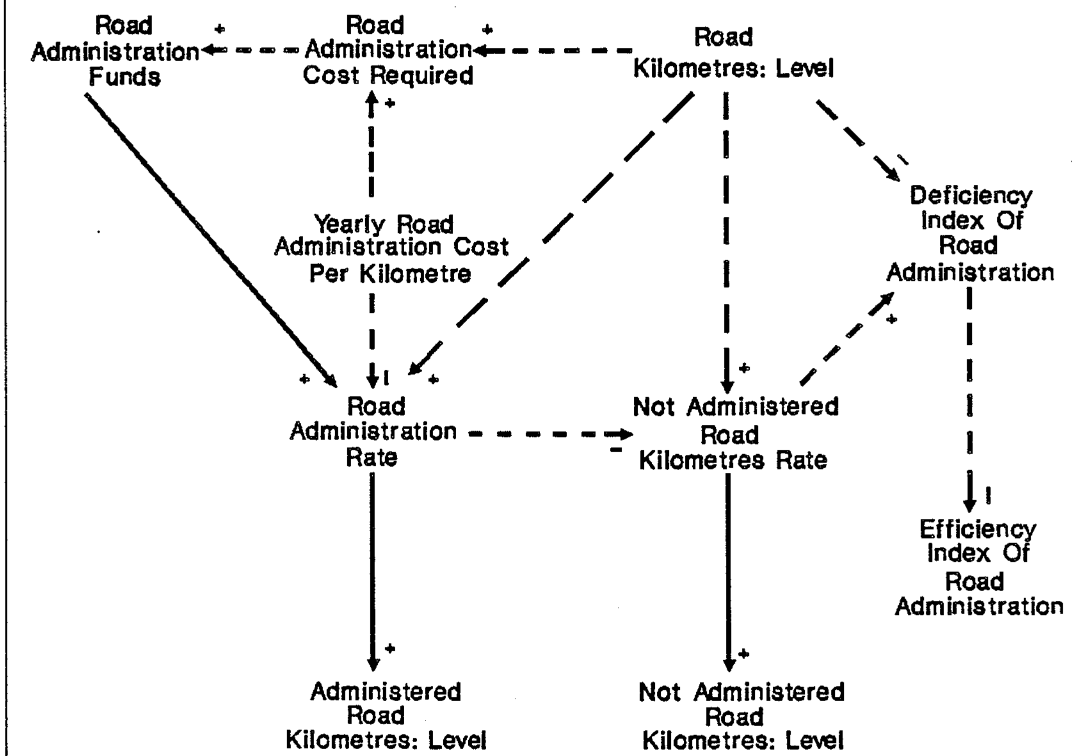

Fig. 3: Road Administration Activity

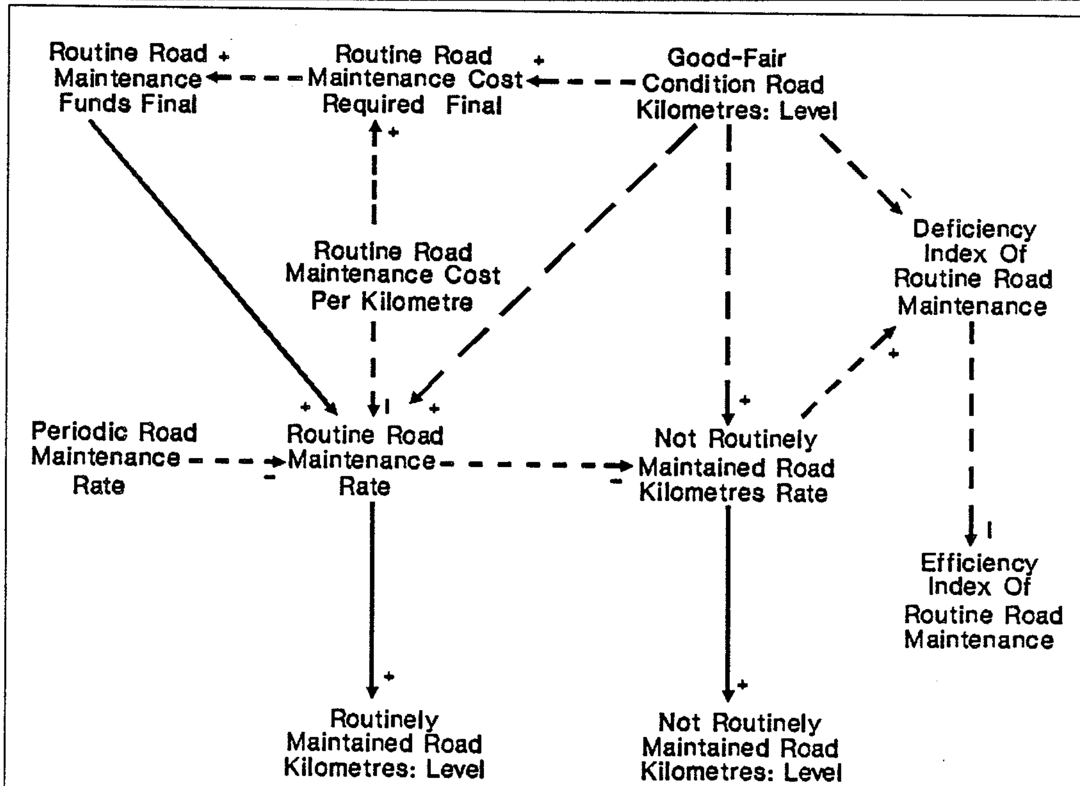

Fig. 4: Routine Road Maintenance Activity

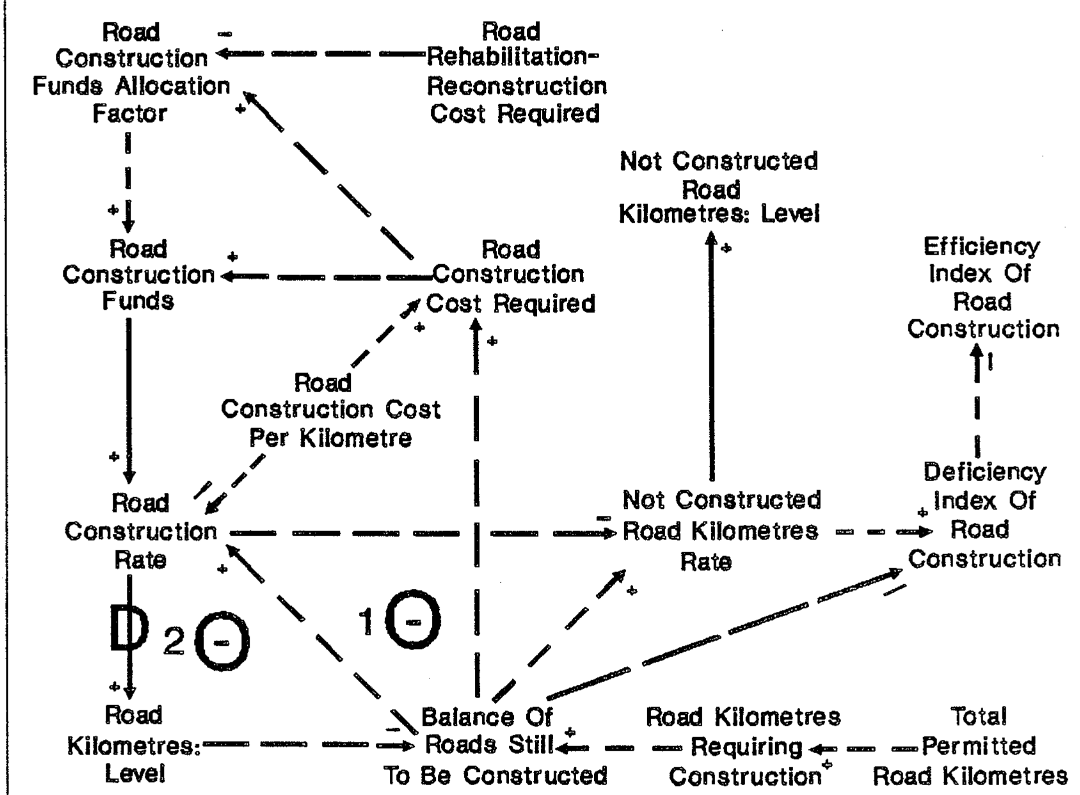

Fig. 5: Road Construction Activity

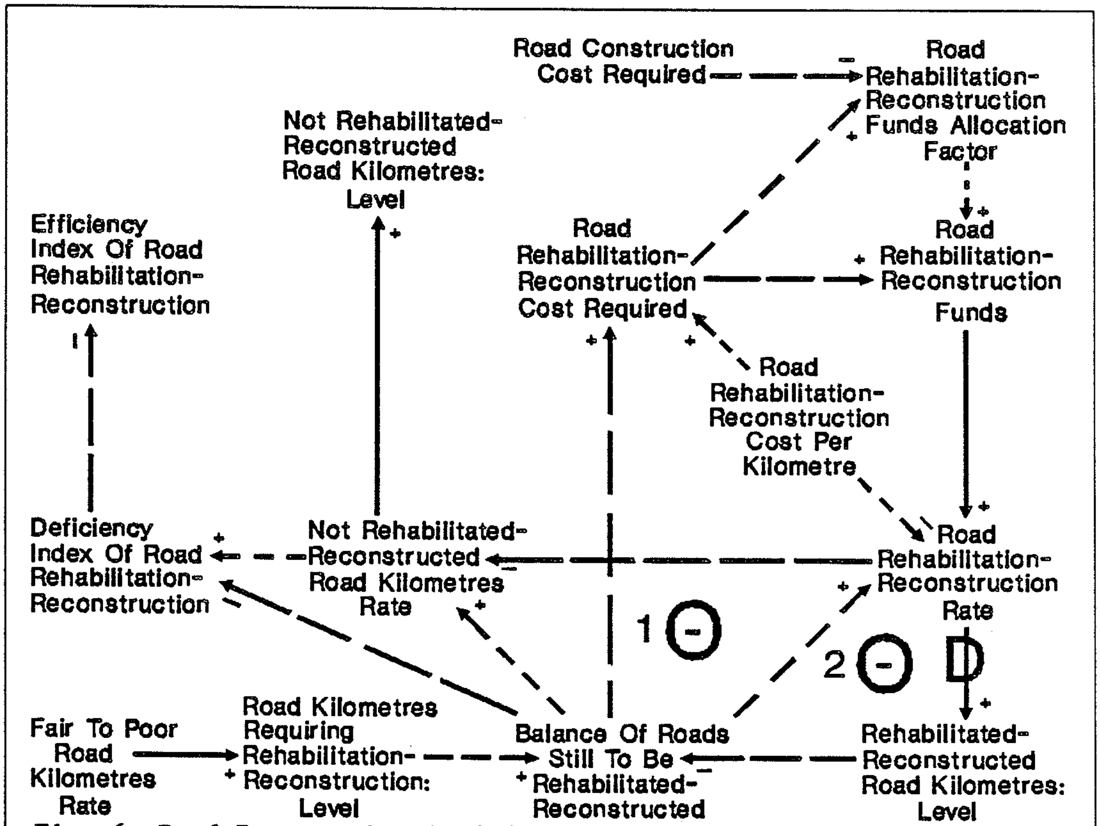

Fig. 6: Road Restoration Activity

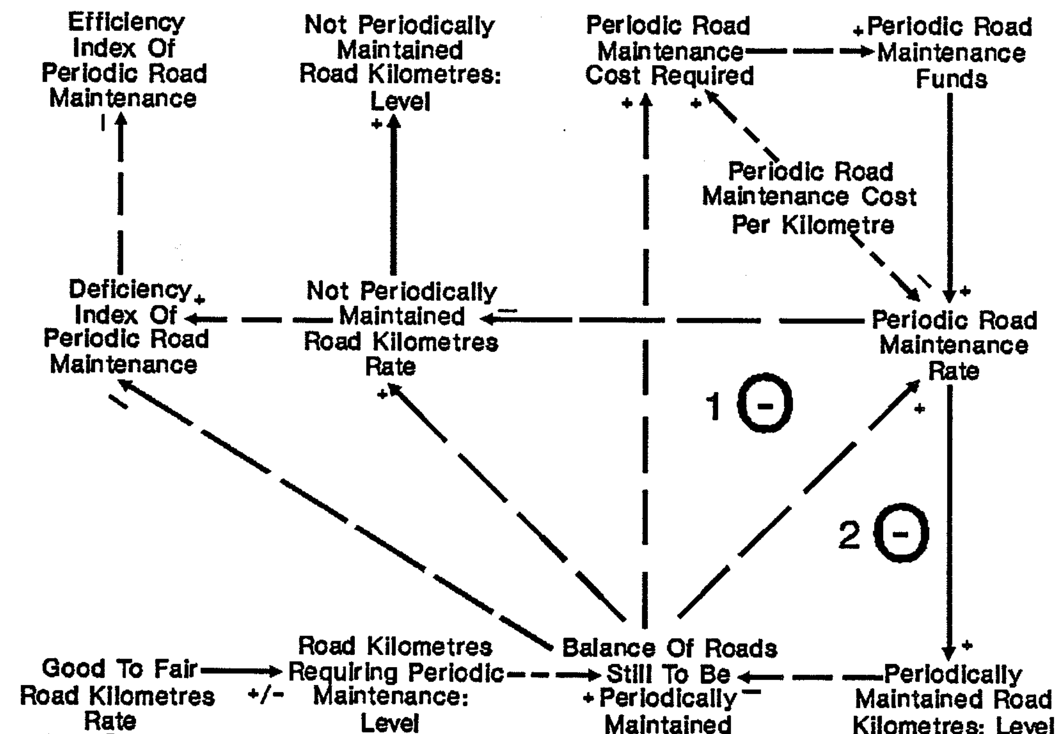

Fig. 7: Periodic Road Maintenance Activity

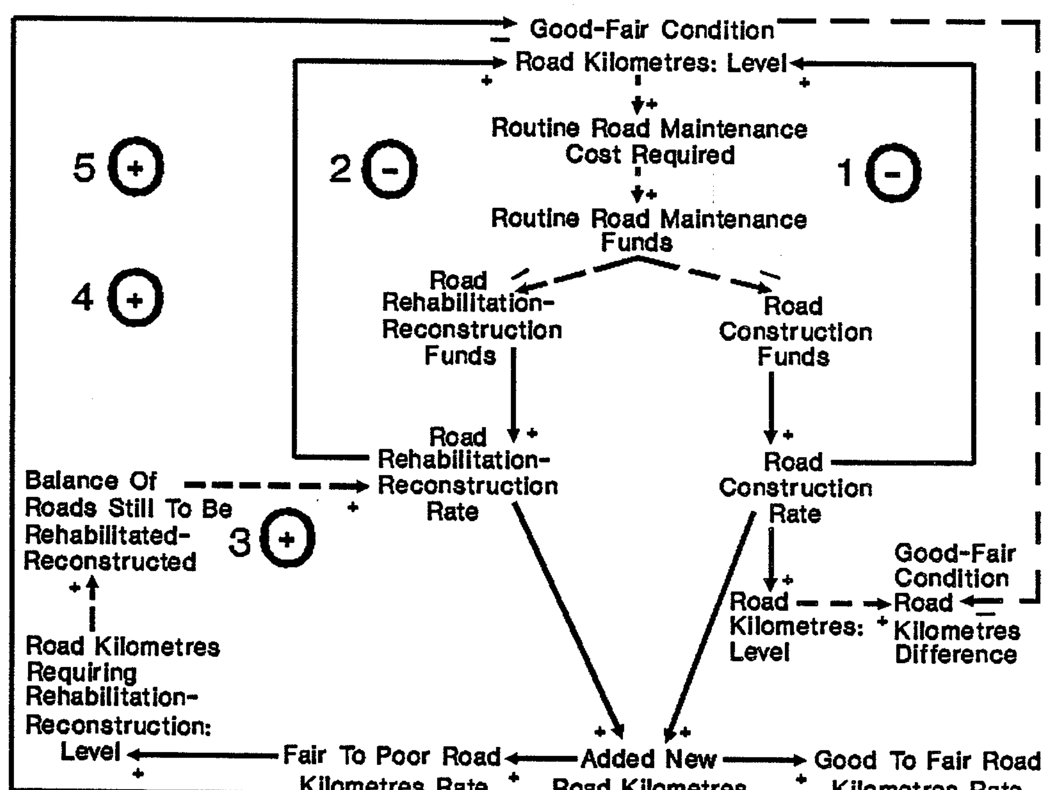

Fig. 8: Road Kilometres Starting New Life Cycles

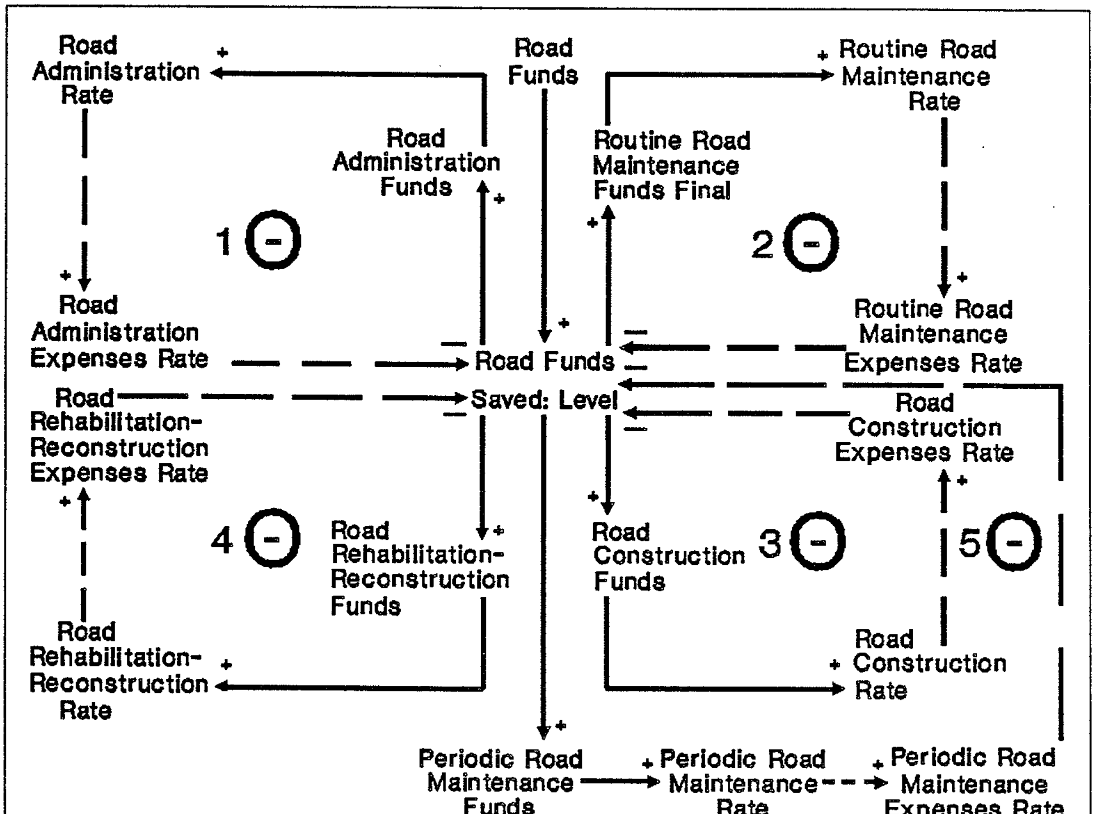

Fig. 9: Recycling of Saved Road Funds

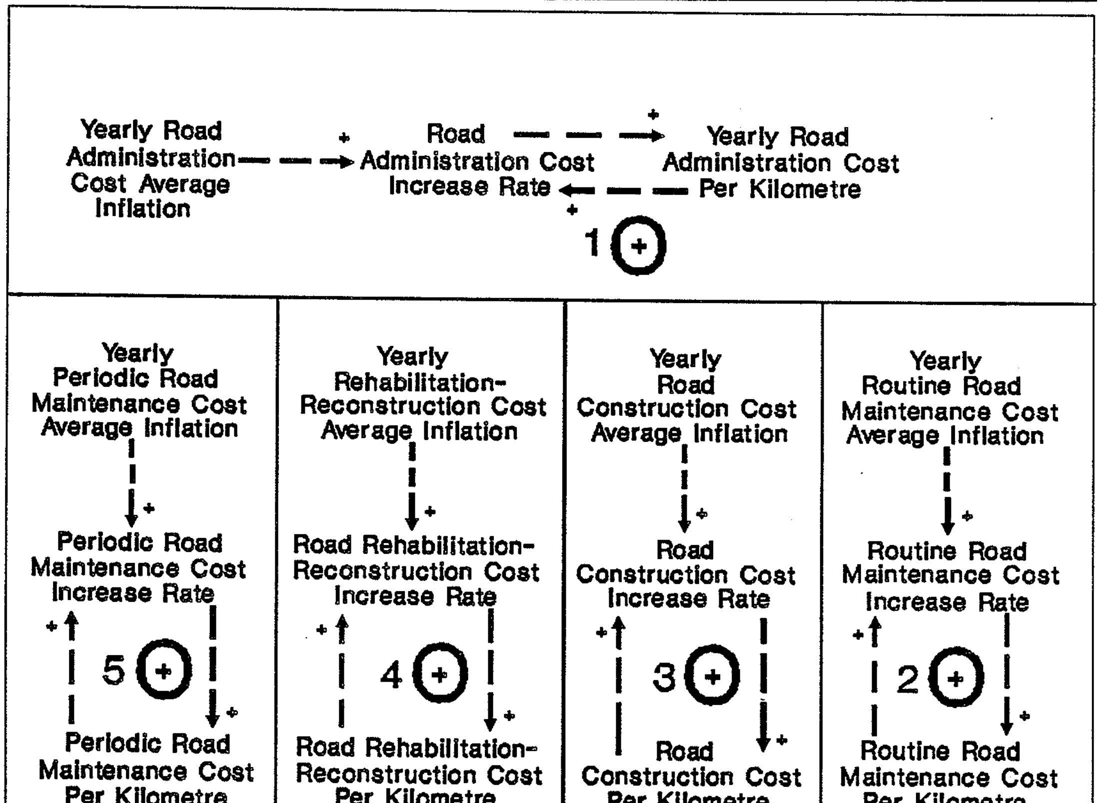

Fig. 10: Unit Costs and Inflation Rates of the Road Activities

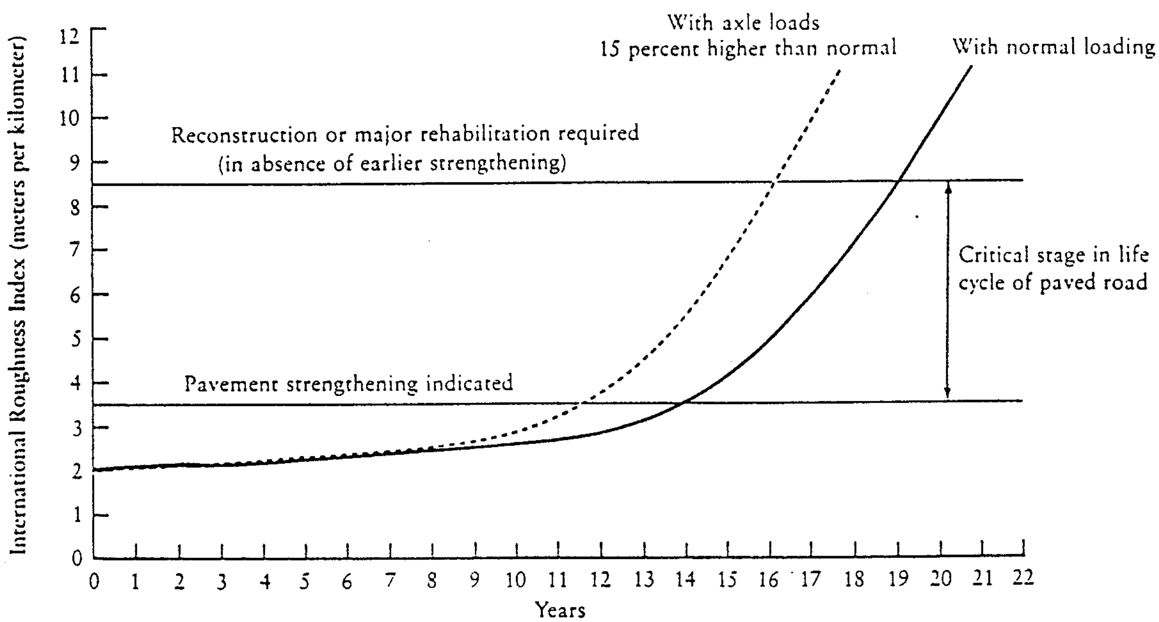

Fig. 11: Deterioration of Paved Roads Over Time
Source : (Harrel 1988)

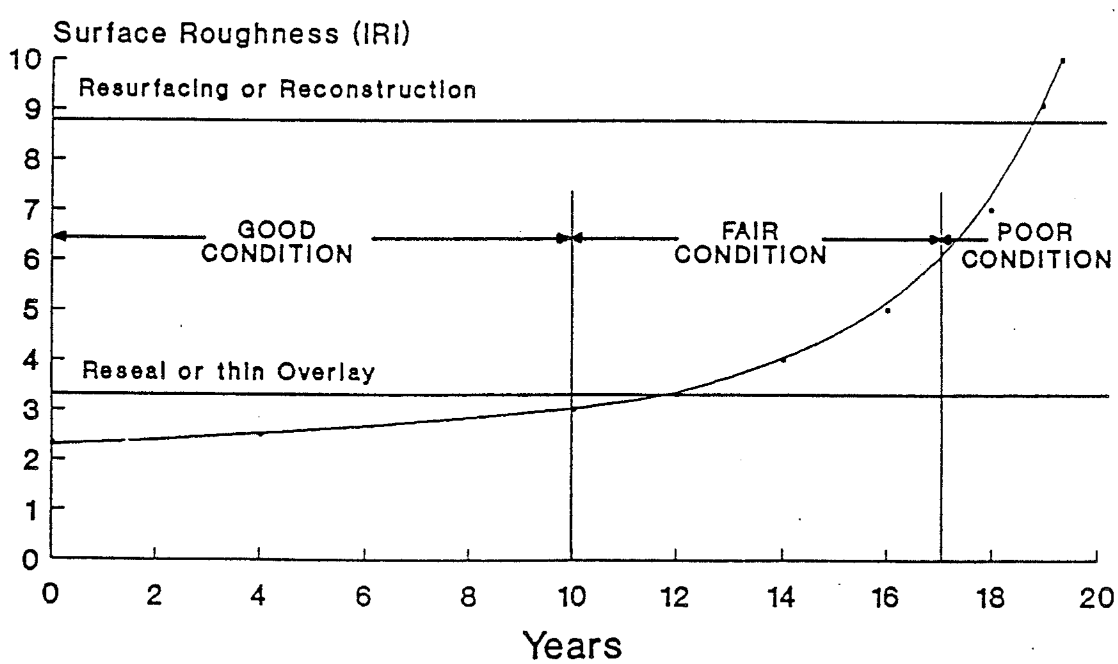

Fig. 12: Condition of Paved Roads Over Time
Source : (Bhandari 1988)