A Method of Road Pavement Condition Projection

Occasional Paper

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FOREWORD

Detailed strategic planning for roads is important not only because of the high cost of road repair and construction but also because of the long-term effects of routine decisions. The consequences of current maintenance policy may be felt for the next thirty years. However, the management of Australia's roads is characterised by a paucity of usable strategic planning information. Such information as exists is fragmented and dispersed.

This Paper describes an exploration of the long-range projection of road pavement condition using a technique that was expected to require only readily available data. In this technique, a Markov chain approach was used to represent the opposing effects of road wear and road work in the changing condition of pavements.

The technique was designed to show the consequences of sustained application of selected maintenance policies and in that connection the results of this initial work are promising. They suggest that the approach can be developed to be of use in the management of road pavements and similar assets.

This study was the work of the Bureau's Planning and Technology Branch. Ms A. Boskovitz was responsible for the mathematical formulation of the approach, and Mr C.M. Plant conducted the road condition and roadwork analyses. The study was designed and directed by Mr A.J. Emmerson following the outline of a study concept proposed by Mr C.R. Sayers.

Acknowledgements are due to the officers of the various State road authorities and the National Association of Australia State Road Authorities who provided data and commented upon the methods and intermediate results.

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SUMMARY

This Paper presents a method of analysing the relationship between road pavement condition and roadwork, for the purpose of examining the effects of future maintenance policies.

Road pavement deterioration is a probabilistic phenomenon. To date there have been no time-series collections of statistics from which the probabilities of deterioration can be adequately derived for the whole of Australia by conventional means. A key element of this study was the development of a method of estimating those probabilities from the available data.

This method of estimation, and the projection method subsequently applied, rested on describing changes in the road system in terms of a Markov chain. The calculation sequence adopted was one permitting pavement condition and road work projections to be made for a variety of maintenance policies.

A unique feature of the method is a definition and arrangement of variables intended to permit low quality data to be accepted, while still providing conclusions useful for strategic planning.

In this method the pavement condition of the road system is described by the proportion of the total road length that 'requires' certain generic types of work. For the purposes of the study, a road length was held to 'require' work if its pavement condition was the same as or worse than that of pavements which the State road authority had repaired in the past.

The method was used to make projections in this study by:

- calculating rates of pavement deterioration, in the absence of maintenance, that corresponded with the experience of 1972-81;
- assuming, in the absence of information to the contrary, that those deterioration rates would apply in the future; and
- combining those rates with both realistic and hypothetical maintenance policies to give changes in pavement condition from the condition measured in 1980-81.

The numerical work undertaken was primarily an exploration of the method's potential. Accordingly, only a limited set of sealed rural and outer urban roads was examined, using data from Tasmania and Victoria. Because of some residual uncertainty in the theory, but mainly because of insuperable voids in the available elementary data, the numerical results must be regarded as no more than tentative. The results are, however, broadly consistent with less analytical observations.

According to the results derived from Tasmania, if present maintenance policies continue, the proportion of sealed rural arterial road requiring reconstruction is projected to increase to about 21 per cent over the next ten years despite increasing annual amounts of roadwork. To hold overall road condition in its present state would require rates of reconstruction approximately double those of the recent past.

In Victoria, the more limited set of roads analysed appeared to be in better condition. Holding overall State Highway pavement condition at its present quality is projected to require a reconstruction rate approximately equal to that of the recent past.

The method explored in this study results in a useful and comparatively simple tool for examining the general effects of maintenance policy, once an initial calibration

is established. Reasonable calibration is just possible for some Australian roads using currently readily available data, and could be made accurate and straightforward with an appropriate data base. Such a data base would take some time to develop, but would be simpler than the existing collections.

CHAPTER 1—INTRODUCTION

In 1982, BTE began a program of work aimed at establishing whether substantial changes in resource allocation are likely to be required to maintain the present Australian road system. This work included an exploration of forecasting methods suited to readily available information.

The method of pavement condition projection described in this Paper was devised in an attempt to answer questions on future pavement condition of the type that might be posed by a road maintenance or road funding agency in developing long term plans. The thrust of these questions would be to determine, in State-wide terms, the pavement condition that would result from the adoption of any selected maintenance policy for the next ten years, and the road work that would be entailed. The range of maintenance policies to be examined would include that of the recent past and that necessary to hold the pavements in their present condition.

This Paper:

- describes the principles of the projection method;
- evaluates the method by identifying the assumptions made and describing the sensitivity of the projections to some of those assumptions; and
- presents some numerical results illustrating the method.

AN OUTLINE OF THE METHOD

There are pronounced differences between the method explored in this study, those now used for pavement condition projection in Australia, and many of the textbook methods of maintenance theory. The differences stem from four points of methodology.

Firstly, road maintenance and condition models should permit multiple definitions of failure (that is, of the need to repair) in order to accommodate the different types of repair work done in practice.

Secondly, experience suggests that the use of continuous analytical expressions for the probability of deterioration or failure as a function of time should be avoided, especially with multiple definitions of failure.

Thirdly, to provide the management tool sought it was necessary to distinguish between the effects of maintenance and the effects of pavement deterioration mechanisms, not only in the projection of condition, but also in the interpretation of past condition data.

Fourthly, because of the limited data available and the context in which the results would be used, a detailed behavioural model was neither practicable nor necessary and a 'aggregate model' was adopted.

Aggregate Models

The method used in this study may be summarily described as consisting of the following steps:

- break the State's road system into sets so that, from maintenance management viewpoint, the roads in each set are uniform;

- find how much road in a set changed from one condition to another in an extended period of time;
- find how much road work was done on the set in the same period of time;
- use this information to find effective average rates of deterioration for the set in the absence of maintenance, and the effective average rates of road work; and
- project the pavement condition of the set forward from current values on the basis of these rates.

The method treats roads with what may be called a aggregate or holistic model dealing with the properties of roads en masse rather than in detail, and which directly models effects rather than causes.

The model is aggregated in two senses. Firstly, the very many parts of the system being studied are combined and the system is treated as though it consisted of only two components, a road subsystem and a maintaining agency.

Secondly, each component is described in terms of observed phenomena rather than in terms of the mechanisms actually at work. In other works, the effects of the operation of the actual mechanisms are aggregated and regarded as phenomena which are properties of the component. The use of aggregate models is a standard engineering technique and a common everyday approach to complex issues. In the present instance, the component properties are, broadly, for the road subsystem, pavement condition and deterioration rates, and for the maintaining agency, rates of repair.

An important consequence of this approach is that the method to be described is able to deal, not with the characteristics of pavements and traffic, but only with two properties of a roads system; and not with the actions of a State road authority, for example, but only with the output of an entire maintenance system including the funding agencies.

Aggregate models are simple, easily visualised and easily modified. Workable models can be generated from data of poor quality. They are usually taken as being completely deterministic and it was largely for these reasons that such an approach was adopted for the study of pavement condition. These models lose predictive capability when the component properties selection do not adequately *represent* the causal mechanisms at work. They become more predictive if the model laws are *derived* from rules known to apply within their components, but this derivation is not always necessary for reliable representation.

In this study, the aggregate model chosen is one having sufficient discernment to be able to address the matters in question but one which does not *directly* represent causal mechanisms and is not derived from them. Its operational rules will be adequately predictive only so long as there is no disturbance in the road system.

Pavement condition descriptions

Rather than use a set of continuous variables to describe pavement condition, the method adopted for this study uses a number of discrete conditions. These conditions have descriptors such as 'requires reseal', or 'requires reconstruction'. If the conditions are defined carefully this technique permits multiple definitions of failure.

Use of the word 'requires' clearly introduces the notion of currently acceptable standards for pavements. This wording was chosen deliberately as a means of permitting variations in those standards to enter the study.

More than one discrete condition descriptor may apply to a particular length of road. The surface may 'require resealing', for example, and the substructure 'require work to restore pavement strength'. In this method, lengths of road which have the same set of condition descriptors are said to belong to the same pavement condition 'state'.

This Paper will return to the selection of the most appropriate condition descriptors and states. The point to be made here is that the method deals with the length of the road network in each condition state.

State changes

A section of road may change condition state either through wear and tear or through roadwork. If these influences are separately identified, it is possible to project the proportion of road in each state by starting with a known initial proportion in each state and accumulating the annual changes.
The annual change in the length of road in a state can be expressed by a simple equilibrium relationship of the type:

Annual change in a state = annual length entering into that state through roadwork and deterioration, less annual length exiting through roadwork and deterioration.

Progressive, year-by-year, solution of such an equation was the general basis of the method adopted for projecting condition.

The rates of exit and entry for a particular state are dependent upon the length of roads in other condition states. The rate of surface improvement depends, for example, on the rates both of resealing and reconstruction and therefore, conceivably, on the length of roads requiring those types of work. The consequence is that a set of simultaneous equations must be used to describe the annual change in pavement condition. These equations are most easily expressed in matrix notation.

The resultant system is one of a type known to mathematicians as a Markov chain and some of the techniques of Markov chain theory can in fact be used. The principal reasons for choosing such a technique were that it simplified the manipulation of a complex set of conditional probabilities, and that the interior details of the calculation processes were highly visible and easily related to physical phenomena.

In any one year, portions of the road length in any specified state (that is, in a specified condition) will experience sufficient change of condition to move to some other states. The fraction of the length in a state that moves to another particular state in one year is known as the 'relative frequency' for that transition, or more loosely as a 'transition frequency'. When evaluated in the long run, these transition frequencies may be regarded as the probability of a length of road moving from one state to another in one year. They are the coefficients in the set of simultaneous equations, and when expressed in matrix notation become the 'transition matrix'.

The projection method assumes that the annual rates of state-to-state changes are all known and are constant over time. That is, the transition long-run frequencies or probabilities are assumed not only to be known, but also to be fixed, pro tem. The justification for this assumption is presented later in the Paper. Prima facie, the most likely value of the transition frequencies are those observed as averages in the recent past. Transition frequencies other than these may be used to examine extremes or confidence limits for example, or to reflect changing conditions.

It is implicit in this concept that the rate at which a road changes condition is dependent more upon its current condition than on any other variable, such as age since construction. In fact the definition of condition in terms of the work required to restore to as new is a key concept in this method.

Determining initial state vector and transition frequencies

The term 'state vector' is used in this study to describe the set of numbers which are the proportions of the total road system in each pavement condition state at a specified time. It is thus a short form description of the road system as a whole. The 'initial state vector' is the state vector at the beginning of the analysis.

The term 'transition frequency' has been introduced as the proportion of the road length in a particular state which changes to another particular state in each year. The 'transition protocol' for a system is the set of rules defining the transitions which actually occur and their precedence or sequential arrangement.

There are, broadly, two techniques by which prevailing transition frequencies may be determined. In the first, a transition protocol is postulated from first principles. An analysis is then run between two known state vectors and the matrix of transition frequencies deduced iteratively. This technique does not always provide a unique solution.

In the second technique, extensive detailed time series data are used to determine whether there is a definite transition protocol and if so, to then calculate the frequencies. This is a difficult exercise requiring extensive, consistently well cross-referenced and detailed data. If the states are so defined that the transition protocol is known, this task becomes simpler, but no less data demanding.

In BTE's experience, road system analyses have been characterised by a paucity of consistently well cross-referenced detailed data and this second technique was considered impracticable. For example, the method requires a knowledge of how much road, in the system under study, would have deteriorated from one state to another in each year had there been no maintenance, that is, the 'intrinsic deterioration rates'. State road authorities (SRA) do not have records of this type. They have some records from which the state vector at the end of each year could be estimated and used to obtain the net deterioration transition frequencies for the year. Deriving rates of deterioration in the absence of maintenance from that data would entail adding the roadwork done each year to this change in state vector during the year. In view of what was known about the road condition and roadwork records held by the State road authorities, the study team was not confident that such a year-by-year derivation of deterioration transition rates could be achieved in the time available. Thus, the iterative technique was adopted during this study. It need not be adopted in future applications of the projection method.

If the proposition that intrinsic deterioration rates can be regarded as statistically predictable is accepted, and particularly if they are regarded as constant, year-by-year derivation of transition rates is not necessary. It is sufficient to use a rate derived from just two condition surveys separated by, say, ten years in time. The 1972 Australia Road Survey and the present National Association of State Road Authorities (NAASRA) data bank were suitable sources and were used for that purpose.

The required parameter was kilometres of state change per year per kilometre of road in that state. (Or, the probability that a road length, having reached a certain state, will leave that state in the next increment of time.) Because the length of road in each state is always changing, condition surveys taken ten years apart will not provide that parameter accurately unless the annual change in state is known; that is, unless the annual difference between the kilometres of intrinsic deterioration and the kilometres of improvement is known.

This annual difference was not available from the data. However, the assumption that intrinsic deterioration rates are near constant, the intention to use a constant effective average maintenance policy, and the knowledge that state vectors for mature road systems are near equilibrium permitted a constant annual change of state to be assumed for the purpose of obtaining initial approximations to transition probabilitiies. These concepts are addressed in more detail in Chapter 2. A calibration exercise was conducted between the 1972 and 1981 state vectors to correct any error arising from this and other assumptions.

Because the history of *work* on sealed rural roads was expected to be reasonably well documented at an aggregate level (owing to the financial accounting requirements), this study used time series data to obtain the frequencies of transitions resulting from roadwork. This necessitated pavement condition state definitions and a corresponding transition protocol that matched the categories of roadwork used in SRA records.

Because the available data on roadwork does not specify the condition of each section of road before it was worked on, a substantial amount of algebra was required in deriving past rates of deterioration. The general process, as described in Chapter 4, amounted to solving for 25 transition frequencies described by only 13 equations.

The necessary rational assumptions were made and many of these were based on the premise that past road maintenance had been efficiently conducted. For example, it was assumed that reconstruction had been undertaken only on those roads that required reconstruction. The consequences of this and other assumptions are discussed later in this Paper.

The initial state vector from which the projections in this study proceeded was derived from the 1981 roads inventory data in the current NAASRA data bank This source was chosen because it was expected to have a known and adequate structure consistent between the States of Australia.

Characteristics required of condition descriptors and states

The pavement condition descriptors chosen for this study, and the resultant pavement condition states, were required to have the following characteristics:

- they must be mutually exclusive and collectively exhaustive;
- they should reflect road user and road authority perceptions of pavement condition;
- there should be a simple and well defined protocol of transitions between states;
- they must permit adequate discrimination between roadworks with different unit costs;
- they must adequately represent the conditions which influence the type of roadwork done and the rate at which it is done;
- there should be substantial correlation between the condition states and the data structure of the NAASRA inventory;
- there should be substantial correlation between each of the transitions due to roadwork and the roadwork descriptions used by the SRA in their annual summaries of work done; and
- they must reasonably reflect the deterioration behaviour of pavements.

The next two chapters of this Paper discuss these characteristics.

CHAPTER 2—ROAD PAVEMENT BEHAVIOUR

AN INTRODUCTION TO PAVEMENTS

The principal function of a road is to provide a surface with shape and frictional characteristics that permit vehicles to be controllable and, along with their contents, to remain undamaged while travelling at the desired speed. Pavements are constructed to ensure that roads will fulfill this function reliably and durably, so that there is little loss of function over long periods or with changing circumstances, and so that there is no loss of function without warning.

The pavement preserves the surface shape of the road by preventing disruptive pressures being exerted on the underlying natural surface, while retaining its own shape. The concentrated loads on the surface caused by the passage of a vehicle are diffused by the beam-like effect of the pavement acting as a relatively stiff plate. The pavement retains its own shape by being sufficiently strong to resist crushing and cracking. Road engineers identify two types of pavement: the 'rigid' and the 'flexible' according to the materials of construction and the consequent stiffness relative to the natural surface.

Very little road is constructed from highly cohesive materials such as steel from which nearly rigid beams are easily made. More usually they are made from naturally occurring material which is much less cohesive[1] in bulk. The science and art of road construction lies then in causing innately noncohesive materials to reliably and durably transmit the shear and consequent tensile forces necessary for strength and for beam rigidity commensurate with the demands of the natural surface. Any reduction in the ability to transmit these forces results in relatively larger localized deflections to the detriment of the road's function.

In pavements constructed from crushed rock, as are typical in Australia, the cohesion in the bulk material is derived principally from the geometric interlocking experienced as one piece tries to move over another under load. Clearly, the more intimate is the contact between pieces (the fewer and smaller the voids or dislocations) the move apparently cohesive is the bulk material. The cross section of an Australian road pavement is shown in Figure 2.1.

Interlocking is enhanced by choosing stones of correct shape, by gradation of stone sizes, and by compaction. In some parts of a pavement, interlocking may be supplemented by adhesion resulting from the use of binders or cements. Cohesion is reduced by the inverse of those processes, such as deterioration in stone shapes, removal of stones of a certain size, the creation of voids, and loss of strength or adhesion in binders.

All the roads examined in this study were 'sealed roads'; that is, roads covered by a structurally thin layer of bitumen mixed with fine stones. The function of this layer is to waterproof the pavement and to provide a wearing surface which is more durable than that provided by a pavement unprotected from abrasion by traffic. Unless applied as a heavy overlay (more than 40mm thick) the bituminous wearing and sealing course is not expected to contribute materially to the strength or stiffness of the

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1. In this context the word 'cohesive' has its common usage meaning rather than the technical meaning of soil mechanics.

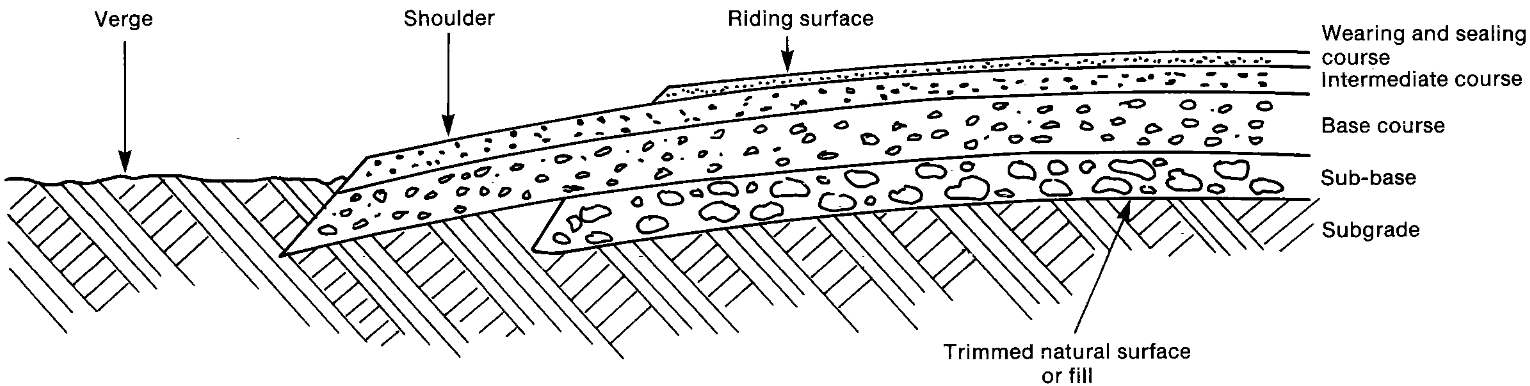

Figure 2.1—Elements of pavement construction

pavement structure. The important characteristics of this layer are then, its impermeability, its resilience, and its frictional qualities.

Consideration of the principal functions of a road pavement and its seal suggests that there are three fundamental modes of failure. The first is a loss of bending stiffness leading to disruptive pressure on the local natural surface and to shape changes. The second is permanent deformation of the pavement itself resulting in surface roughness. This deformation may be accompanied by cracking, or may take place 'plastically', meaning, without evident cracking or other void creation. The third failure mode is loss of frictional qualities.

There are three fundamental mechanisms by which failure in these modes occurs.

The single application of a very high load which can create permanent deformation may also result in cracks which reduce bending stiffness. Failures due to this and similarly unpredictable causes are commonly called 'chance overloads' or 'chance failures'.

Failures strongly influenced by the duration of the cause are known as 'wear out'. Repeated high loads, which by internal abrasion change the shape and size of stones in the pavement thereby reducing bending stiffness, may also displace material by erosion or plastic flow, resulting in loss of frictional qualities and or greater surface roughness.

Climatic and other features of the natural environment cause chemical and physical changes in road pavements and the subgrade which also lead to failure. Bituminous binders lose resilence by these mechanisms and, most importantly, conventional pavement materials lose cohesion when permeated by water.

In practice the distinction between failure mechanisms is not so clear cut as presented here. Real failure mechanisms are almost invariably a mixture of these fundamental mechanisms.

Once a pavement has begun to fail, deterioration accelerates. The cracks which are created result in less cohesion and thence lower strength and stiffness and higher localized forces. Cracks are propagated or enlarged by even small repeated loads. Cracks and voids facilitate the entry of water. Increased roughness results in higher dynamic loads from vehicles, and so on.

THE PAVEMENT LIFE CYCLE

Maintenance terminology

The term *serviceability* is synonymous with current functional capability. Deterioration such that any of several predetermined serviceability criteria is no longer satisfied is the general definition of failure. Durability denotes the rate of change of serviceability and reliability with time.

Preventative maintenance is work initiated when durability no longer satisfies preset criteria. Usually the work done is of the type that will retard deterioration. This work is relatively inexpensive.

Repair maintenance is work initiated by failures. The work done is of the type that will restore serviceability. In ideal repair maintenance the work done results in as-new serviceability.

Repair and preventative maintenance are not fully separable concepts, for two reasons. Firstly, a loss of durability almost in, and the restoration of serviceability usually restores durability. Secondly, preventative maintenance actions may coincidentally restore serviceability.

Age and serviceability

By and large, the life of a road is taken to be the length of time for which it can be kept serviceable without being rebuilt.

In this context a road is said to be serviceable if it is able to satisfy the requirements of the transport task for which it is *currently* used. Road serviceability is a function of pavement serviceability, traffic capacity and composition, traffic speeds, and vehicle operating costs and delay costs. Note that traffic may grow to exceed the road's capacity, necessitating upgrading and the attendant reconstruction, even though the pavement may not have reached the end of its useful structural life.

The measure of a pavement's functional adequacy, or serviceability, may be its roughness, or some combined index of this and other parameters. One such index is the 'Present Serviceability Index' developed in the United States of America which relates measurable pavement characteristics (roughness, cracking, patching, rutting) to the average user's opinion of its serviceability.

Pavement structural life estimates are based on judgements about the worst pavement condition acceptable, and on estimates of the time taken, based on projected cumulative traffic volumes, for this terminal condition to be reached. The life predicted depends also on the initial pavement condition and the type of traffic likely to be encountered. The stochastic nature of pavement durability plus the uncertainties in the prediction of cumulative traffic mean that estimates of pavement life have some uncertainty. There is some finite probability that the serviceability of the pavement will fall below the minimum acceptable level before the end of any design life nominated. That is, a proportion of the pavements will fail prematurely and have to be rehabilitated or reconstructed.

Pavement condition and therefore serviceability is a statistically distributed function of pavement age and maintenance history. Pavement serviceability decreases gradually with the accumulated effects of traffic and the passage of time. It is periodically partially or fully restored in relatively sudden steps, each step resulting from a maintenance action such as resealing, or reconstruction. In general, the level of serviceability will begin falling immediately after each action, declining slowly at first and then more rapidly.

Figure 2.2 gives a schematic representation of the age versus serviceability relationship and of the life phases through which a section of pavement may conceivably pass. Not all possible paths are shown, as they multiply rapidly at each node of the maintenance activity decision tree. At the end of the pavement life, rehabilitation and reconstruction strategies are shown as alternatives. The different immediate effects of resealing, rehabilitation and reconstruction on pavement serviceability and the effects on future serviceability can be seen.

It is not necessary that rehabilitation or reconstruction be delayed until the pavement degrades to terminal serviceability. There is notionally an optimal serviceability at which certain types of road work should be undertaken to maximise the value of some chosen life cycle cost effectiveness objective, though the incorporation of such an 'optimal intervention level' into a practical maintenance policy seems to be an ideal yet to be achieved. Figure 2.3 illustrates part of the reason by showing the type of serviceability-age envelope to be expected from the accumulation of small variations in deterioration rate, permitted minimum serviceability at repair, and repair effectiveness. Although a mean path is shown in the figure, the actual mean path is in fact unknown. It is practically impossible to obtain the algebraic description of this path, usually necessary for optimisation, from observations beginning with a mature road system. While the mean serviceability at various pavement ages may be measured in a mature system, these values are only tenuously linked to the trajectory followed by a typical section of road, as shown in Figure 2.3.

For comparison with Figure 2.2, the type of approximation to the reality of pavement

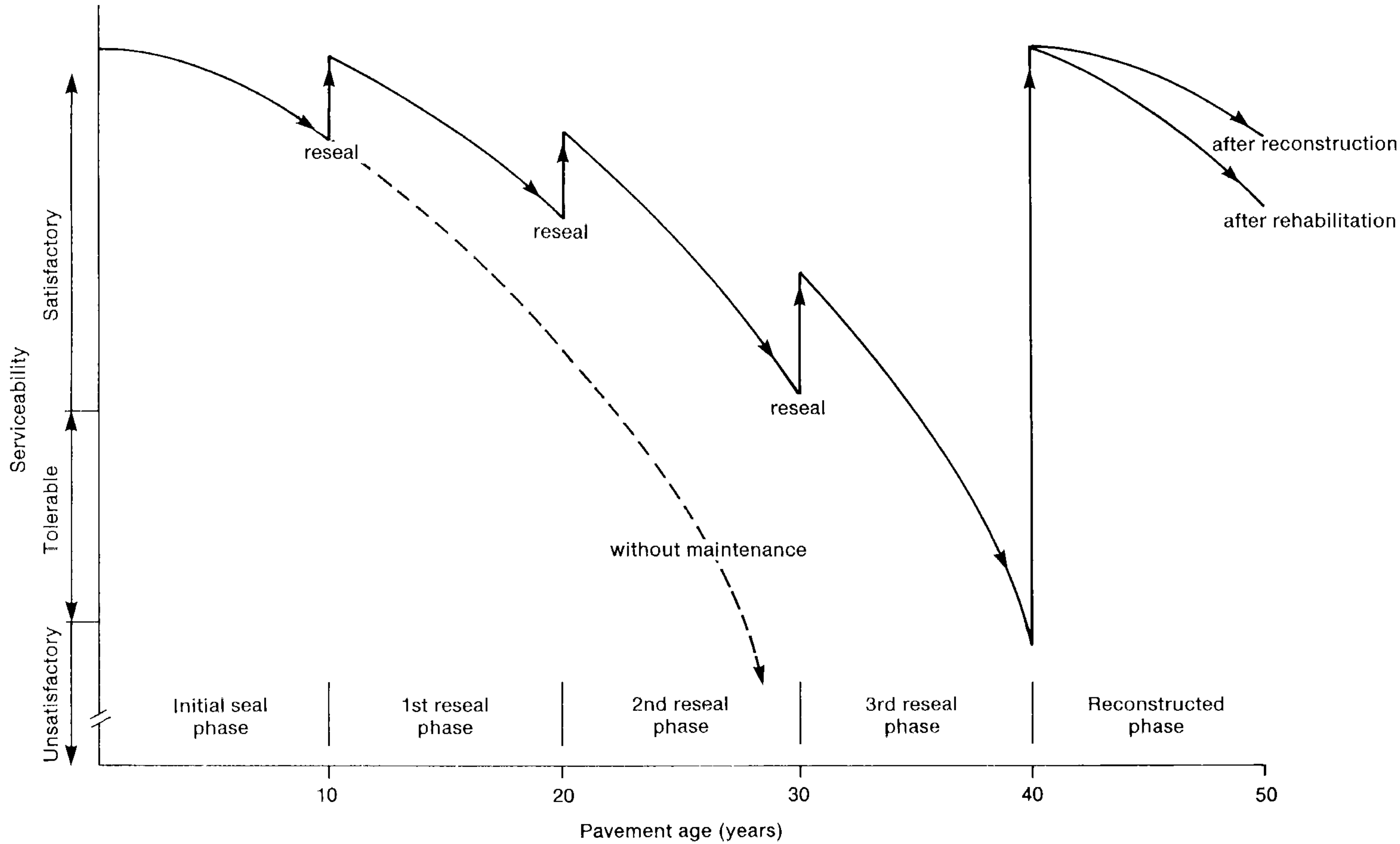

Figure 2.2—The pavement life cycle concept

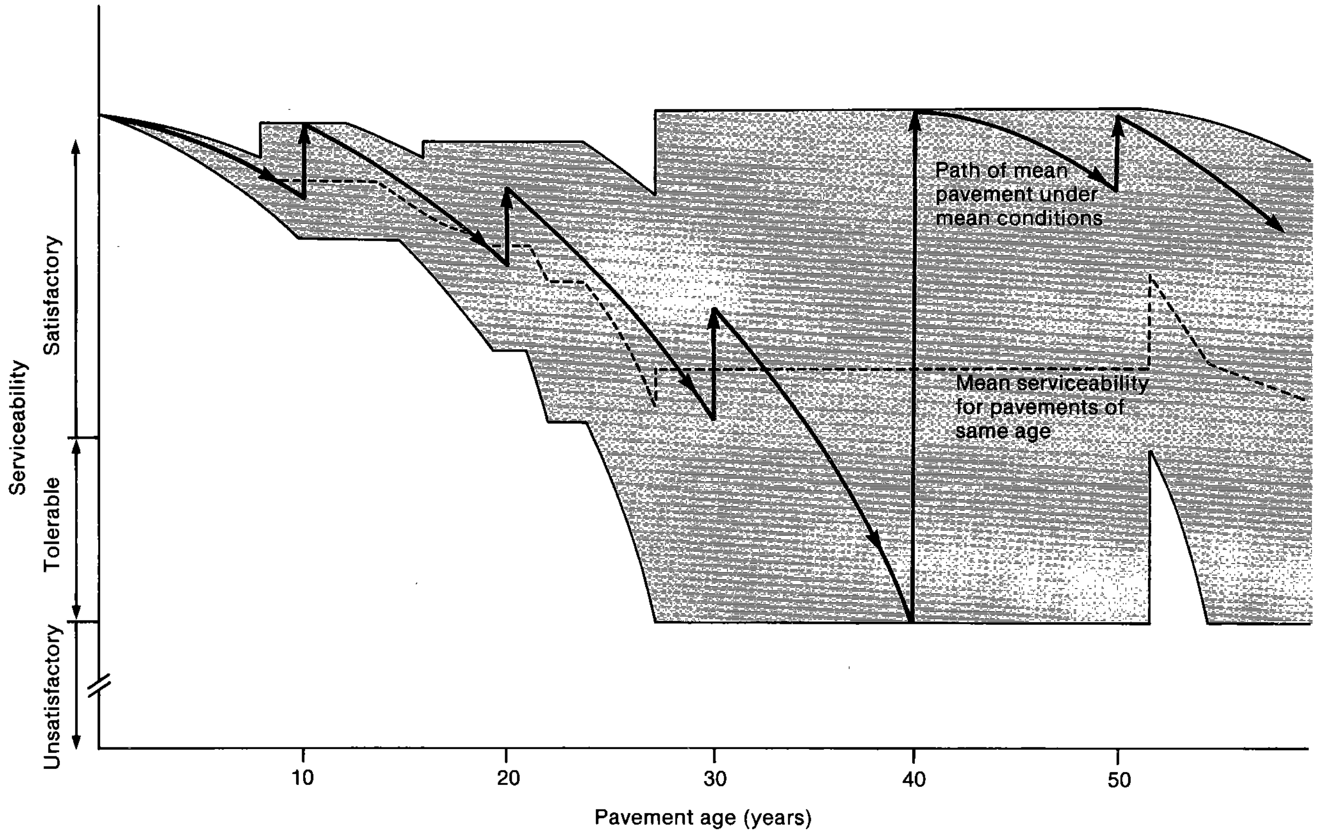

Figure 2.3—Pavement life cycle envelope concept (for pavements constructed at same date)

deterioration that was in effect adopted during this study is presented in Figure 2.4. The Markov chain method can be thought of a calculating the probability that a length of road will follow any such possible path.

It must be emphasised that Figures 2.2 and 2.4 depict the behaviour of a single section of road. When many sections of road are considered together, and particularly with ideal repair maintenance, the road stock exhibits a condition of mixed wear such that the perceived rate of change of overall condition with time is small and the annual number of failures is approximately constant. This situation persists so long as time-since-reconstruction is reasonably uniformly distributed over all road lengths. If the average time-since-reconstruction increases over the years, then the annual number of failures will increase to an extent governed by any natural preponderance of wear-out over chance failure.

This quasi-static or near equilibrium condition of a mature road network not only coincides with the tendency of Markov chains to proceed mathematically to equilibrium, but also permits assumptions which are important in the derivation of past rates of deterioration. Appendix II deals further with this matter.

Phases in pavement life

The following are descriptions of the pavement condition[1] likely to prevail in each of the life phases defined in Figure 2.2.

Initial seal phase

Immediately after construction the pavement is structurally sound and bending stiffness is high. Surface roughness as measured by an instrumented vehicle[2] is low, less than about 60 counts/km. There is little or no surface cracking evident. The width of any cracked area is less than 10 per cent of the width of the sealed surface. The depth of any longitudinal depressions or ruts is less than 5mm. The bitumen at the surface shows no sign of oxidation and no small stones have been loosened from the surface.

As the pavement ages any construction faults will become evident as pavement distress. A loss of surface material called 'ravelling' may occur because of inadequate bitumen content, waves in the surface may result from poorly applied surfacing, there may be depressions because of inadequate compaction and there may be some cracking. Climatic factors induce oxidation of the bitumen and hence disintegration of the wearing course by stripping, weathering and, with traffic, potholing. Maintenance carried out to this stage is mainly patching of potholes and possibly seal enrichment with a fog coat. Structural damage is not so likely at this early phase and roughness will probably not be high. A reseal may be desirable to retard deterioration of pavement serviceability. This would provide a protective layer to offset oxidation, decrease water penetration, and in general preserve the asset.

After about 10 years, resealing may be the selected treatment when the road condition has the following characteristics:

- bending stiffness is still high;
- roughness has increased to 80 or more counts/km;
- less than 5 per cent of the surface has been patched;
- surface discolouration and some loss of fine stones is general;

1. In presenting these descriptions, the authors were guided by the Australian Road Research Board Road Condition Rating System (Porter and Armstrong, 1980) and by the rating system proposed in Yeaman and Lee (1979), and by Commonwealth Bureau of Roads and National Association of State Road Authorities (1971b).

2. In the recent past the roughness of roads in Australia has conventionally been measured with an instrumented vehicle in which 15mm of vertical movement between the chassis and the rigid rear axle is regarded as one count.

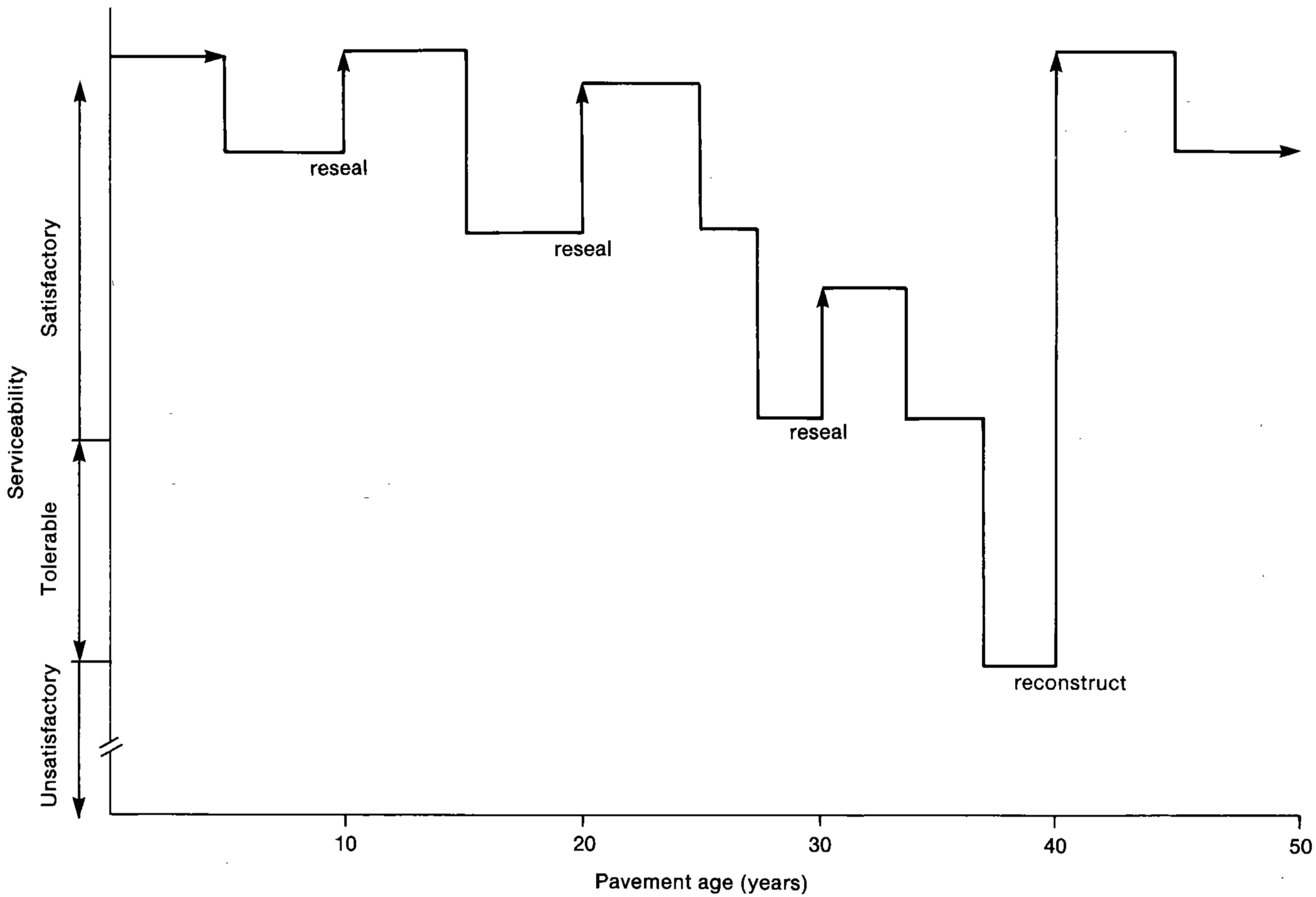

Figure 2.4—Typical pavement life cycle in study concept

- disintegration of the surface (stripping and ravelling) is excessive, extending over 25 per cent of surface area;
- average rut depth is between 5mm and 10mm;
- areas with interconnected cracks are moderately large (up to 15 per cent of area), longitudinal and transverse cracks are quite evident but they are less than 2mm wide;
- skid resistance is lower than desired owing to polishing action or bleeding of bitumen through the mix; and
- up to 15 per cent of the length of the edge of the sealing course has broken away in widths up to 75mm.

Isolated instances of structural failure may occur (eg due to the ingress of water) necessitating premature local reconstruction of the pavement.

First reseal phase

The pavement structure now consists of the pre-existing pavement plus a wearing course restored by either:

- a sprayed seal (usually a single application of bitumen binder and aggregate) or;
- an enrichment seal of bitumen water emulsion or solvent thinned bitumen in two or more applications to restore binder and to seal tension cracks, or;
- a thin overlay (less than 40mm) of plant mixed bitumen and fine stones to correct surface deficiencies.

These treatments restore the appearance and to some extent, the durability and the smoothness of the road, but not usually to the same quality as a newly constructed road and they do not restore strength or stiffness.

In time, the defects noted in the initial phase will reappear and, in addition, so called 'reflection cracking' is likely to occur in the new top layer due to movements, deflections and cracks, in the lower layers. As the pavement is older, time-dependent distress is now more significant. The cumulative effect of cyclic traffic loadings may be evident.

Moisture penetration is also more likely as time passes, causing loss of sub-grade strength, initially at the edges and shoulders. The likelihood of there having been overloads increases with time and shear distortions may occur. Maintenance activity during this phase would entail more patching of pot holes, repair of edge defects and shoulders, and a levelling of deformations in the road surface.

When the pavement reaches an unacceptable condition and is scheduled for its second reseal, it may typically be in the following state:

- reduced bending stiffness;
- roughness is more marked, up to 100 counts/km;
- patching is moderate to extensive (6–15 per cent of area);
- visible cracking is as extensive as it was just before the first reseal;
- average rut depth is minor to medium (10–15mm); and
- 15 to 30 per cent of the length of the edge of the sealing course has broken away in widths up to 100mm.

Second reseal phase

The pre-existing structure is overlaid with a new wearing course, as in the first reseal. Some levelling work may be carried out prior to this to smooth out the surface distortions and reduce roughness so that the serviceability can be restored to an acceptable level.

At the end of the second seal life, the physical condition and distress patterns will be much like those described for the first-seal end condition. Some additional deterioration mechanisms may have become more obvious with the passage of time: thermal stresses leading to longitudinal and transverse cracks, and pot holes; moisture entry leading to edge cracking and edge drop-off, to rutting, and to swelling and shrinkage cracks; poor bonding between the reseal layers leading to slippage cracks; and stripping of wearing course due to loss of adhesion in the presence of water. The road condition is typically:

- bending stiffness noticeably reduced;
- roughness most marked, up to 120 counts/km;
- patching moderate to extensive (6-15 per cent);
- cracking as widespread as before but the cracks have opened to widths of between 2mm and 5mm;
- average rut depth medium (15mm); and
- edge failures along 15-30 per cent of length but now encroaching up to 200mm on to the riding surface.

Third reseal phase
The initial serviceability of this life phase is similar to that described for the previous reseal phases; a reseal layer has been applied to the existing pavement, once necessary corrections have been made to surface distortions, to provide a water-proofing and wear-resistant cover.

At the end of this phase, conditions are usually such that another resealing will neither satisfactorily restore serviceability nor curtail excessive future preventative maintenance costs. That is, resurfacing is no longer an economic solution and the pavement requires rehabilitation or reconttruction. Mulholland (1980) found that rehabilitation or reconstruction was preferred when the number of seals and reseals exceeded three in number and the annual preventative maintenance effort exceeded 40 manhours/km. Cracking and distortion will now indicate deep-seated structural deterioration of the pavement. The cumulative effect of traffic will have induced cracking and rutting in heavily-trafficked roads, thixotropic hardening of the binder will have induced block cracking on low-traffic roads, movement and settlement of the sub-grade will have caused shear deformation in the pavement structure and reflection cracking in the surface layer. Upheaval may have occurred due to swelling of expansive clays. Roughness will lead to increased dynamic loading and accelerate the development of corrugations and potholes. Road condition at this stage may have the following profile:

- bending stiffness is low;
- roughness exceeds 120 counts/km;
- patching over 15 per cent of area resulting in a poor ride and low water-resistance;
- interconnected cracking is extensive (over 15 per cent by area), longitudinal and transverse cracking may be widespread and with crack widths over 5mm;
- rutting medium to major (15-30 mm); and
- edge failure severe (over 30 per cent of edge length and more than 200mm wide).

Rehabilitated phase
Rehabilitation is work carried out along the existing alignment and width to improve the upper layers of the pavement. As defined by State road authorities it does not include sealing work less than 40mm thick or work less than 60 metres in length or 500 square metres in area. Rehabilitation can be:

- overlays greater than 75mm thick, both dense and open-graded;

- recycling or reworking of the pavement surface, either in situ or at a central plant, with or without admixtures; and
- combination of recycling and overlays.

It is reasonable to assume that the surface manifestation of pavement distress will be eliminated (ie, edge fretting, cracking, distortion, disintegration, and frictional deficiencies); hence serviceability will bp restored to the equivalent of a new pavement. However, rehabilitation does not cure the loss of structural strength arising from physical changes in the sub-grade, sub-base and base (eg, basal moisture penetration) so a rehabilitated road cannot properly be considered to be in the same state as a new road and these structural defects will accelerate the future loss of serviceability.

Reconstructed phase
During reconstruction the pavement structure is excavated, the sub-grade re-compacted and new pavement material or recycled material is used to construct the pavement layers. It is often, but not always, supplemented by an upgrading of the road, ie, widening, strengthening, realignment, and gradient changes. In the reconstructed state, the road is equivalent to a new road with initial seal.

CHAPTER 3—PAVEMENT CONDITION STATES AND TRANSITIONS

STATE DEFINITIONS

In satisfying the prerequisites so far outlined for the definition of pavement condition states, three descriptors were chosen; namely S, relating to the quality of a road's wearing and sealing course, P relating to the quality of its underlying structure, and G relating to the adequacy of the operational aspects of its geometry.

These descriptors are each permitted to take different values. Thus, in the notation adopted, S may take the values Si and Siii; P the values Pi, Pii, Piii; and G the values Gi, Gii and Giii, where Si, Pi and Gi represent the best condition and Siii, Piii and Giii the worst. The condition of a length of road is denoted by a combination of specific values for each of these descriptors, such as Si Pii Gi.

Until deficiencies in the available data made themselves felt, the preferred method of combining these descriptors to define condition states (ignoring geometry for the moment) was as follows:

Si — A road in this condition would be one requiring no work on either pavement or wearing course[1].

Siii Pi — A road in this condition would be one requiring resealing to rectify surface defects and to waterproof the sub-structure.

Siii Pii — A road in this condition would be one requiring light work to restore sub-structure strength and to rectify sub-structure deformation, or one where the surface irregularities and cracking require a heavy bituminous resheet; a thin reseal would not shift a road from this condition.

Si Pii — This would be the condition of an Si Piii road that has had light substructure work or of a road that has been restored from condition Siii Pii by the application of a bituminious resheet; the surface quality is satisfactory but the sub-structure strength has not been fully restored.

An essentially equivalent condition could be reached by a road with a sub-structure that deteriorated prematurely while the wearing course remained sound.

Siii Piii — A road in this condition would be one requiring heavy work to restore sub-structure strength and rectify sub-structure deformation, the sub-structure condition would be manifested in surface irregularity and cracking.

Si Piii — This would be the condition of a road that had been restored from condition Siii Piii by bituminous resheeting; a road could not deteriorate directly into this state.

This set of condition state definitions could not be implemented explicitly because the available data contained only the most elementary descriptions of pavement condition. Specifically, the only description of wearing course condition was elapsed 'time since last reseal'. This precluded differentiation between the effects of simple resealing and heavy bituminous resheet both of which reduce the 'time since reseal' to zero and thus would, ostensibly, produce the same surface condition. Moreover,

1. That is, no work which is sufficiently costly to justify inclusion in this study.

the best available description of pavement structural condition was surface roughness. This complicated the definition of states since it is known that heavy bituminous resheet will substantially reduce roughness whereas simple resealing will not.

In the face of these limitations the pavement descriptors were given supplementary definitions of the following type:

Si —less than about nine years since last bituminous surfacing work;

Siii —about nine or more years since last bituminous surfacing work;

Pi —roughness less than, say, 80 counts/km;

Pii —roughness from, say, 80 to 120 counts/km; and

Piii —roughness greater than, say, 120 counts/km.

The difference in surface quality resulting from simple resealing compared with heavier resheeting cannot be discerned with these definitions. For a given time since resurfacing the resealed road will be near one end of the roughness range for a state and the resheeted road nearer the other.

However, these definitions do permit the higher durability of the resheeted road to enter the analysis, albeit subsumed in an overall value.

Considering now the operational geometry; a road in the Gii condition was defined as one requiring minor construction work or 'improvements', such as widening on crests and curves. A road in the Giii condition was defined as one requiring substantial new construction or 'upgrading', such as realignment which abandons much of the existing pavement. Deterioration to the Giii condition is the result of changes in traffic.

In so much as this was a pavement condition study, the effects of geometric condition needed to be included only to the extent that they altered the frequency or cost of the roadwork undertaken. In the context of this study, the Gii condition was reckoned not to have these effects. The Giii condition was reckoned to influence the probability of work being done on only those roads in the Piii condition.

In the first instance, Giii was given the supplementary definition "not meeting the NAASRA design recommendations for the prevailing functional class, daily traffic, and terrain".

Thus, the following pavement condition states emerged:[1]

State 1	requires no work	Si Pi any geometry
State 2	requires resealing	Siii Pi any geometry
State 3	markedly deteriorated	Si Pii any geometry
State 4	requires rehabilitation or similar work	Siii Pii any geometry
State 5	structure unacceptable	Si Piii and Gi
State 6	structure and geometry unacceptable	Si Piii and Giii
State 7	requires reconstruction	Siii Piii and Gi
State 8	requires upgrading	Siii Piii and Giii

Although the condition descriptors were given the supplementary definitions described, the intent of the primary definitions was preserved. That is, a road's condition was still held to be described by the road work required to refurbish it.

1. Descriptions of work required are indicative only. They are not intended to conform with NAASRA definition of work types.

As will be seen in Chapter 4, the importance of the exact supplementary definitions of the condition states lies in the accuracy with which past road work can be said to have been done on roads in particular states.

The pavement condition at which roads are perceived by a road authority to require work will change with time and between authorities. The age and roughness values initially selected for the supplementary definitions were chosen because they typified the condition at which pavements are generally thought to require work in Australia. During subsequent analysis, these values were changed from the initial typical values by only the smallest amount necessary to match what appeared to be the practices of individual SRAs.

The state to which a road shifts as a result of deterioration or road work can also depend on the supplementary state definitions. In the selection of these definitions care was taken to ensure that such dependence did not unduly distort the transition protocol derived from the primary definitions.

It should be emphasised that use of the somewhat factitious condition state definitions was necessitated by the structure of the existing data base describing Australian roads. This need not be so in future were there to be a data base which recorded, not roughness and seal age etc as at present for each length of pavement, but simply the type of work necessary to restore the length to as-new. As will be seen in Chapters 5, 6 and 7 and in Appendix II however, this would require a more rigorous application of precise standardised terminology than is at present evident.

STATE TO STATE TRANSITIONS

A length of road may change state either through deterioration or through road work. With eight pavement condition states, there are, prima facie, 56 possible transitions. In this study only 25 of those transitions were regarded as admissable and these are shown in Figures 3.1 and 3.2. In referring to the transitions the notation adopted is that, for example, U38 means the intrinsic deterioration from state 3 to state 8; and W75 the transition from state 7 to state 5 caused by road work. The numerical value assigned to a symbol is the probability or long term relative frequency with which road lengths make that transition in one year.

Of the possible deterioration transitions, U15, U25, U16, U26, U17, U27, U18 and U28 were ruled inadmissable on the grounds that a pavement is most unlikely to deteriorate in one year from a near new structural condition Pi to one requiring reconstruction Piii.

U35 and U36 were initially ruled inadmissable because it was considered most unlikely that a pavement deterioration from Pi to Piii could occur without deterioration of the surface. If the supplementary definitions of S as 'time since resurfacing' is applied, then U35 and U36 must be admitted.

Transitions U23, U45, U67 and U46 were ruled inadmissable because a road cannot deteriorate into a better condition.

The model was idealised to some extent by an assumption that roadwork has not been and will not be undertaken on road lengths with wearing and sealing courses in good condition. The probabilities of work being done on roads in states 1, 3, 5 and 6 were therefore set to zero and this was done by regarding work transitions out of those states as inadmissable.

Roadwork was supposed not to degrade pavement condition. This led to the elimination of transitions W78, W47, W48 and W23 to W28 inclusive.

It was held that pavement structural deficiencies could not be rectified without renewing the wearing and sealing course and accordingly transitions W42, W82, W72 and W84 were ruled inadmissable.

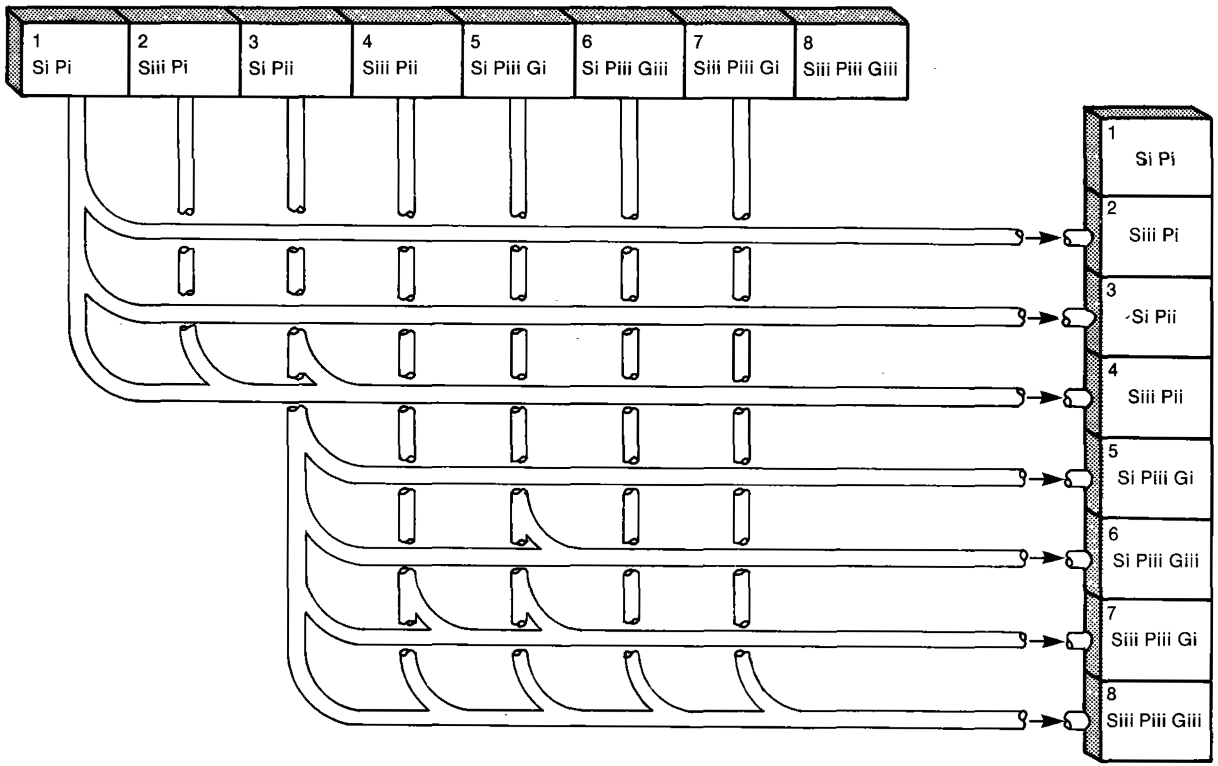

Figure 3.1—Intrinsic deterioration transitions (Uii)

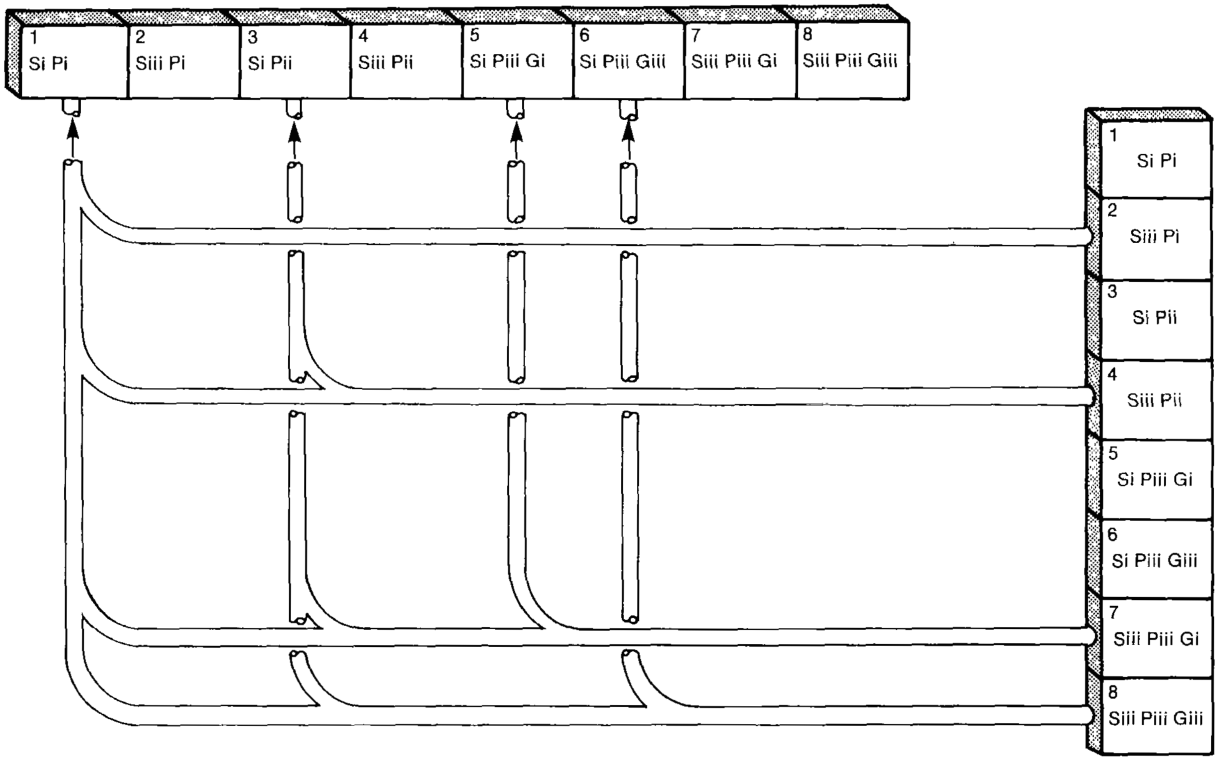

Figure 3.2—Work transitions (Wi)

W67, W85 and W87 were ruled inadmissable on the grounds that geometric deficiencies of the type characterising states 8 and 6 could not be rectified without rectifying the pavement structural condition.

There are several transitions which could result if a road were to deteriorate and to be worked on in the same year. These include the transitions from state 4 to states 5 or 6 and from state 2 to state 3.

Consider, however, a road in state 2, with roughness corresponding to Pi and with a deteriorated seal. If in a particular year such a road were resealed it seems improbable that the roughness would rise to the Pii range in the same year.

Similarly, resurfacing a road in state 4, with roughness corresponding to Pii, could be expected to prevent roughness increasing to the Piii level in the year of resurfacing. Accordingly the probabilities of these transitions were set to zero.

There is a fourth transition of this type, that from state 7 to state 6, representing resurfacing work accompanied by a deterioration in geometric adequacy but no significant improvement in roughness. The probability of this transition was conceivably non-zero. However, this is the probability that a length of road will be resurfaced in the particular year its geometry becomes inadequate and was expected to be negligibly small. Accordingly, the frequency of this transition was also set to zero.

In a more rigorous analysis many of the transitions ruled inadmissable would have been retained. In this study, however, the diversity in the data being used to derive past transition frequencies was not sufficient to permit retention of more than 25 transitions.

Note that transitions described as deterioration of geometry, such as U78, do not represent physical changes in the road, but model the changes in traffic which render existing road geometry inadequate.

The method of assigning reported roadwork to each of the roadwork transitions will be discussed in Chapter 4.

CHAPTER 4—ANALYTICAL APPROXIMATION TO TRANSITION MATRIX

OUTLINE OF TECHNIQUE

The following explicit questions evolved from the exploratory framework of this study as described in Chapter 1.

If the maintenance policy and intrinsic deterioration rates effective between 1972 and 1981 were to apply constantly from 1981 onwards, what would be the pavement condition in the ten succeeding years and what would be the condition after twenty years? What annual roadwork would this entail in the first ten years?

If the 1972–81 intrinsic deterioration rates prevail, what maintenance policies would be needed after 1981:

- to hold the roads in the 1981 condition; or
- to prevent continual accumulation of structurally degraded pavement?

In this context, 'maintenance policy' is taken to mean the proportion of road in each pavement condition state that is worked on in specified ways during a year.

This chapter discusses the derivation of the average maintenance policy and intrinsic deterioration rates effective between 1972 and 1981. What was sought was the constant maintenance policy and intrinsic deterioration rates which, if applied from 1972 onwards, would have given both the road conditions observed in 1981, and the total road work reported in each category for the 1972–81 period, using the Markov chain method for condition projection.

The methodological kernel of the whole study was the technique of deriving this matrix of transition frequencies so as to adequately represent the behaviour of selected road sets over the past ten years.

These transition frequencies were derived by:

- finding an analytical expression for the maintenance policy and intrinsic deterioration rates implied by any given annual change in condition and any given set of work rates;
- finding the average annual roadwork and average annual change of condition between 1972 and 1981 and using these in the above expression to evaluate approximate transition rates; and
- modifying the approximate transition matrix so that it satisfactorily predicted the observed 1981 condition from that observed in 1972.

The elements of the matrix are the annual relative frequencies of the road work and intrinsic deterioration transitions, shown in Figures 3.1 and 3.2. In principle, there are many combinations of numerical values of these matrix elements which will transform one given condition state vector into another. The combination required was that which best reflected what was already known about road pavement behaviour.

A set of linear simultaneous equations was developed, in which the unknowns were the elements of the transition matrix and the known constants were the annual road work in kilometres and the actual annual change of length in each condition state. There were 25 unknown elements in the matrix, as specified in Chapter 3.

The equations were arranged so that substituting the observed values of road work and state change during a year gave an initial approximation to the values of the elements of the transition matrix. The derivation of the equations is described algebraically in Appendix I.

The first eight of these equations were derived from equilibrium considerations. The increase in the length of road in a particular state in a year is equal to the length of road entering the state in the year less the length leaving that state.

A further five equations were derived from consideration of the annual roadwork done. The available tabulations of roadwork undertaken annually by the SRAs did not specify the condition of the road before or after the work was done. Accordingly the following distribution of work was assumed:[1]

- all resealing, except for a fraction defined as Lambda, was assigned to the transition from state 2 to state 1, ie to W21;
- all heavy bituminous resheeting plus the fraction Lambda of the total resealing was assigned to the transitions W43, W75 and W86;
- all light structural work was assigned to the transitions W41, W73 and W83;
- all heavy structural work accompanying geometric changes was assigned to the transition W81; and
- all other heavy structural work was assigned to the transitions W71 and W81.

The distribution of roadwork types is illustrated in Figure 4.1.

A further seven equations were derived by making the following assumptions:

- Work done on road lengths that would otherwise have deteriorated from Siii Pii to Siii Piii Gi and to Siii Piii Giii is drawn from the two potential deterioration streams in proportion to the sizes of each stream.
- For road lengths in the Si Pii state and all Piii states, seal deterioration is independent of geometric condition[2].
- For road lengths deteriorating from the Pii condition to the Piii condition, the distribution of geometric condition is independent of seal condition[2].
- The probability of a transition out of the Si Pii state because of seal deterioration alone is the same as the probability of a transition out of the Si Pi state because of seal deterioration alone. (That is, the distributions of seal age in states 1 and 3 are nearly the same.)
- The probability of a transition out of the Siii Pii state because of pavement structural deterioration is the same as that out of the Si Pii state.
- In the Si Pi and Si Pii states, seal deterioration is independent of pavement condition, when seal condition is measured by age in years.

These assumptions, which are elaborated upon in Appendix I, resulted in twenty equations with twenty five unknowns.

Because there were fewer equations than unknowns, several of the less significant work rates were re-expressed in terms of other work rates, with which they were expected to be directly correlated, in the following way:

W75 = Epsilon x W71
W82 = Zeta X W81
W86 = Eta x W81

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1. In Chapter 3 it was assumed that no work is done on roads with sound wearing and sealing courses.
2. The independence of these from one another does not preclude a high degree of correlation between them.

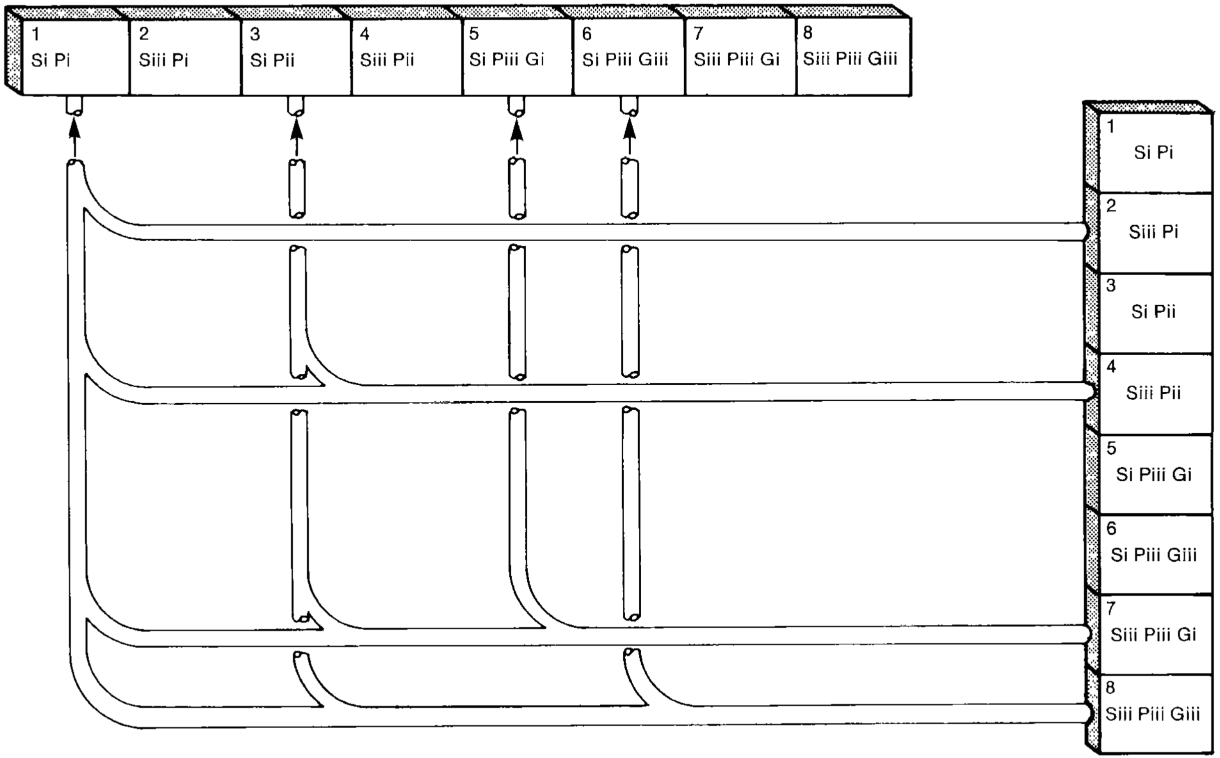

Figure 4.1—Work distribution

Heavy structural work was apportioned to transitions W71 and W81 in the ratio of the lengths of road in States 7 and 8, weighted by a factor Kappa.

The probability of light reconstruction being performed on a length of road in the Siii Piii condition was taken to be independent of geometric condition, that is W73 was assumed equal to W83.

The parameters Epilson, Eta, Zeta, Lambda, and Kappa were then treated as the residual unknowns. They were described by the term 'maintenance policy ratios' and considered to be constant during any analysis period.

These twenty equations were solved to give a value for each of the transition matrix elements in terms of the maintenance policy ratios. The solution is decribed in Appendix I.

Finally, to obtain intrinsic deterioration rates from work and net deterioration rates, it was assumed that the road lengths in a state that were worked on were those lengths that would have deteriorated out of the state during the year, with the exception of the deterioration from Siii Piii Gi to Siii Pii Giii. For road lengths in the Siii Piii Gii state, the probability of their being worked on was taken to be independent of the probability of their geometry deteriorating to give an Siii Piii Giii state.

With these relationships established, the numerical problem became one of finding the correct value of the maintenance policy ratios. That is, the problem became one of finally capturing past maintenance policy, and in doing so, establishing past deterioration rates.

For this purpose a computer program (INTRINSIC) was developed which would repetitively give deterioration rates for various combinations of values of the maintenance policy ratios. Selection of the appropriate combination was aided by the recognition that, since the elements of the transition matrix are probabilities, their values must lie between zero and one. This imposed relatively tight constraints on the admissable values of the maintenance policy ratios, and the required approximate transition matrix was usually quickly obtained.

By trial and error, the constants that gave a transition matrix most closely predicting the 1981 state vector from the 1972 vector were then found. The predictions or projections were made with a second computer program (PAST-FUTURE) that used Markov chain methods.

During the study all of this work was conducted speedily using an 8 bit 64kilobyte personal computer running compiled BASIC under the CP/M operating system. The Markov chain procedures may also be simply implemented using a commercial electronic spread sheet program to aid visualisation of the progress of projections.

LIMITATIONS OF THEORY

Most of the theoretical background to the method being explored has been described by Chapters 1, 3 and 4. Before proceeding with a description of the numerical work, certain limitations of this theory should be acknowledged. Broadly they result from:

- the unknown extent to which the Markov chain process represents actual road system behaviour; and
- the questionable assumptions employed in implementing the Markov chain method.

The most important issues are:

- the likelihood that transition frequencies are not constant but are dependent on which actual lengths of road are in particular states;
- the assumption of maintenance efficiency; and
- the dependence on trial and error calibration.

The discussion of these limitations in Appendix II indicates that it is reasonable to propose, for a limited range of purposes, that a system of road pavements behaves as a Markov chain and that the assumptions made necessary by inappropriate structure of the readily available data are unfortunate but acceptable.

In short, a usable model has been produced; something which is unlikely to have been achieved by other methods, especially as these must perforce rely upon the same limited data base.

CHAPTER 5—NUMERICAL METHODS AND DATA SOURCES

Using the analytical expressions described in the previous chapter to obtain numerical values for the transition frequencies effective between 1972 and 1981 entailed:

- closely defining the road system to be analysed;
- determining its 10 year average condition state vector and rate of change of condition; and
- finding the 10 year average length of each type of roadwork done on the system annually.

Road descriptions were drawn from the 1969-73 Australian Road Survey (ARS) and from the collections of 1981 road data known as the National Association of Australian State Road Authorities data bank (NDB). These were not ideal sources. For example, while the data inventories of the two surveys are similar, they are not identical in their identification and quantification of information, or their coverage of the Australian road system. Moreover, they describe pavement condition less directly than was desirable.

While it was likely that some other existing data collections would have permitted more precise analysis and given more accurate results, and even dispensed with the need for the analytical approximation of Chapter 4, the known collections described only small sets of roads and were unsuited to the study of techniques intended to be more generally applicable.

ROAD SYSTEM DEFINITION

The assumptions implicit in adopting the Markov chain technique under investigation dictated that the roads making up the system to be analysed should be sensibly uniform from a maintenance management viewpoint. They could, for example, all be sealed roads of the same legal and functional classification.

It was also necessary that a description of each road in the system actually appear in both the ARS and the NDB[1]; and that the system selected be one for which annual roadwork rates were known explicitly.

Between 1972 and 1981 road systems changed in several ways:

- new roads and extensions to existing roads were constructed and sealed;
- existing unsealed road sections were reconstructed and an initial seal applied;
- existing roads were closed off;
- existing roads were shortened by realignment;
- roads were reclassified into different functional or legal classes;
- expanding urban boundaries changed outer urban roads to urban;
- roads were reclassified as National Highways; and
- road identification numbers changed.

Before the data inventories could be used in transition rate analyses, it was necessary that any such changes be accounted for, so that a road set common to both 1972

1. For this reason roads constructed after the ARS was conducted could not be included in the analysis.

and 1981 could be identified and used to examine pavement condition changes. The changes in the road system were detected by comparing the coverage of the two surveys on a road-by-road basis. Each road was examined for differences in total length and in sealed length, and for changes in functional class and State legal class.

The NDB road set being generally more restricted than the ARS set, those roads which did not appear in the NDB file were first removed from the ARS data to give a modified ARS file. When roads were found to have changed legal class, they were treated as though they were of the legal class under which they appeared in 1981. Roads which appeared in the NDB but were absent from the ARS as a result of either new construction or new public road declarations, were initially retained in the NDB set of roads. Extensions of the sealed road length by initial sealing of gravel sections of the roads were also retained for the time being.

There then remained differences between the recorded lengths of the roads in a set in 1972 and 1981 but these were due only to new construction, initial sealing and new declarations. Typically, it was not known in what particular year these changes took place, though the lengths of new declaration could be separated from new construction or sealing by references to road authority records. Nor was the condition of roads at the date of their declaration known.

The method of allowing for this length variation is described in Appendix III. The allowance was necessary when comparing 1972 state vectors with 1981 vectors. Broadly, length changes due to new construction and initial sealing were treated as having been additions to condition state 1. The other length changes were assigned to each of the other condition states in proportion to the length of road in each state.

Correspondence between sections of road in each survey could not be readily established and a complete road was the smallest unit used for making length and classification comparisons between the two sets of survey data.

PAVEMENT CONDITION ASSESSMENT

Pavement structural condition

In the ARS, the structural condition of a pavement is described as 'years of life remaining' and is based on visual assessment. In the NDB, structural condition is described in terms of roughness, or, in default, by a 'Present Serviceability Rating' (PSR) which is based on a visual assessment of the road pavement. The year of construction or most recent reconstruction is also listed in the NDB.

None of these parameters directly prescribes the structural work required on a pavement and thus none of them could be used directly to allocate road lengths to condition states. However, acceptable relationships between each of these parameters and work required can be established using roughness as a common datum. It was for this reason that roughness was selected for the supplementary numerical definition of condition states.

The Economics of Road Vehicle Limits (ERVL) Study (National Association of Australian State Road Authorities 1976) found, for the different functional classes of road within each State, a roughness at which reconstruction effectively took place. This was termed the Effective Minimum Tolerability Level. It is a reasonable assumption to take this as the roughness threshold for the Pii state. A NAASRA rating panel has set what are termed Desirable Minimum Tolerability Levels, based on a user discomfort criterion; roughness above this level should prompt some restorative action by the road authority. This roughness may be taken as the upper bound for roads in the Pii state.

Further guidance for the selection of roughness thresholds for each condition state is provided by the NAASRA Improved Model for Project Assessment and Costing (NIMPAC) in which roughness values associated with various types of roadwork are implicit[1]. This model also contains a relationship[2] between roughness and PSR.

The ERVL Study also produced roughness-age relationships. These, or the revised versions produced by later research on the part of several SRAs, are generally accepted as having some empirical validity, albeit with strong reservations in some quarters. They are, for example, used by NIMPAC despite the reportedly poor age-roughness correlation. From an amalgam of this data, a set of supplementary numerical definitions for the pavement structural states was obtained. Examples of these are set out in Table 5.1.

The information collectively provides a way of estimating the mean road age at reconstruction, that is the 'life' of a road. This life can be used with the ARS 'years of life remaining' to obtain in effect the age of road lengths described by the ARS, and hence their roughness, and their structural condition state.

TABLE 5.1—EXAMPLE NUMERICAL DEFINITION OF STRUCTURAL CONDITION; TASMANIAN STATE HIGHWAYS

	Roughness (counts/km)		
NAASRA functional class	*Pi condition requires no structural work*	*Pii condition requires light structural work*	*Piii condition requires heavy structural work*
1	up to 80	80 to 120	above 120
2	up to 80	80 to 120	above 120
3	up to 100	100 to 120	above 120
6	up to 120	120 to 180	above 180
7	up to 120	120 to 180	above 180

The roughness of roads in 1981 is nominally recorded in the NDB, and this was the preferred source used to assign road to pavement condition states for 1981.

For many roads, however, 1981 roughness is not actually recorded in the NDB. In these cases roughness was imputed in one of the following ways:

- correction of an older roughness using a rate of change of roughness with time drawn from the postulated roughness-age relationship;
- calculation from the recorded pavement age in 1981 and the roughness-age relationship; and
- calculation from the recorded PSR, by the method described in the NIMPAC Road Planning Model Appendix B or in the Road Rating Survey of 1971, using the formulae provided there or supplied by the SRA involved.

Seal condition

The condition of a pavement's wearing and sealing course was evaluated on the basis of the number of years since resurfacing. In the ARS, the number of years since resurfacing is not recorded directly. Instead, 'surface condition' is recorded,

1. Specifically, the values of the variables AREC, AREH, RRPW, RRPA, RRPB and RRPS given in the STANDS file of NIMPAC.
2. NIMPAC Road Planning Model Manual Appendix B.

meaning the number of years before resealing is required. This was converted to seal age by subtraction from an average resealing interval calculated from:

- NDB Cost Group Data used in the NIMPAC procedure;
- examination of all 'surface condition' values in ARS; and
- analysis of actual resealing rates

The resealing interval most commonly used was 12 years.

For NDB data, the seal condition was obtained either directly from the listed 'year of resurfacing', or by using 'surface rating' in the same way as the ARS 'surface condition'.

Geometric condition

Geometric condition was assessed by setting the recorded carriageway width and traffic speed against width and speed[1] standards set down in the NAASRA guide 'Geometric Design for Rural Roads'. In this guide, the desirable widths and speeds depend upon road function, prevailing terrain, and traffic volume.

A road length was held to be in the Giii condition if it carried 25 per cent more traffic than recommended by the guide. Where necessary, traffic volumes taken from the ARS and NDB were adjusted by known traffic growth indices.

AVERAGE STATE VECTOR AND AVERAGE ANNUAL CHANGE

A computerised condition assessment of the reduced ARS and NDB inventories resulted in most road lengths being assigned to a condition state, so giving 'preliminary' pavement condition state vectors for 1972 and 1981. The remaining road lengths for which the condition state could not be determined because of incomplete data in the records for these sections were then assigned to states in the following ways:

- If P was known and either G or S was known (but not both), two possible states existed for that section; the road lengths were distributed between them in the proportions evident in the preliminary vector.
- If only P was known, up to four possible states existed; the road lengths were distributed proportionally amongst these.
- If P was unknown, the road lengths were distributed proportionally amongst all the states, regardless of whether S or G were known.

The 1972 and 1981 vectors so obtained differed from one another as a result of the extension or reduction of the total length of the road set, and as a result of road deterioration and repair. The amount of extension or reduction evident was assigned to condition states in the manner already described.

An average state vector for the period 1972-1981, nominally for 1976, was then obtained by linear interpolation, together with an average annual rate of change of road length in each state. This rate of change was reduced to allow for changes in the total length of road in the set which were not caused by road repair or deterioration.

The adjustments to the condition vectors are described in more detail in Appendix III.

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1. So-called 'highway speed' was used from the ARS and 'horizontal curve speed' or 'vertical curve speed' from the NDB.

AVERAGE ANNUAL WORK RATES

The SRAs publish annual reports on the performance of their departments at varying levels of detail. The 1971 to 1982 reports were used in the first instance to give:

- a description of the declared road system under the authorities' control in terms of road length by road classification (legal class, functional class), surface type, etc;
- a description of changes to the road network through re-numbering and reclassification of roads;
- data on the amount of bituminous work, cross-tabulated by type of work and the class of road; and
- records of works identifying the type of work, the extent of the project, the location by road name or road class, and the reason for the work.

The work performed in the road set being analysed was summed under the following headings to give annual averages for 1972–1981:

- Resealing: the application of a sprayed seal to an existing seal, being less than 40mm in depth and not part of staged construction; this included enrichment seals, slurry seals, ordinary spray seals, and some plant mixed work.
- Light reconstruction: work done in isolated lengths (less than 60m in length or 500m^2 in area) on deteriorated sealed pavements, involving digout of the existing pavement structure (either down to the base or sub-base course), renewal and recompaction of pavement material, and resealing. (Such work was included if it was likely to have changed the average roughness of a typical inventory section from Piii to Pii or from Pii to Pi.)
- Bituminous Resheeting: the application of a 50–100mm thick bituminous concrete (asphalt) overlay to an existing sealed pavement.
- Reconstruction: the rebuilding of the structure of a sealed road, using the existing formation for a large proportion of its length and without significantly changing the width, the geometry of the new road then being substantially the same as that prior to the reconstruction.
- Upgrading (widening): work which changed the surface width category of a road was counted if it would have changed the net structural condition of the pavement as measured by ruling roughness.
- Upgrading (alignment): the reconstruction of a sealed road on an improved horizontal alignment or grade on a formation substantially different from the existing carriageway.
- Extension of sealed roads: additions to the system of declared sealed roads, through construction of new sealed roads, reconstruction of existing unsealed road lengths and, initial sealing (often as part of staged construction). Construction to new seal included primer-sealing and initial sealing.

The State road authority annual reports covered a much larger set of roads than was being analysed in this study. The data in the reports were often so aggregated as to preclude their use for the intended road set. When this occurred, supplementary data were sought from the SRA, or, the definition of the set of roads to be studied was altered to suit the available data, before analysis of pavement condition.

FINAL TRANSITION MATRIX AND PROJECTIONS

With the average annual change in pavement condition and average annual work rates established, leading to an approximate transition matrix, the next step was development of a final transition matrix that could be regarded as the matrix effective between 1972 and 1981, and therefore suitable for use in projections of pavement condition.

The criteria for acceptability of this matric were that:

- it accurately transformed the observed 1972 condition state vector into the observed 1981 vector;
- it simultaneously predicted that the total roadwork done between 1972 and 1981 was equal to that observed, in each of the work categories; and
- the relationship between its elements did not deviate markedly from those of the algebraic analysis (more deviation being permitted where the analysis was theoretically weak).

To obtain the requisite matrix, individual elements of the approximate matrix were simply changed 'by inspection' in the manner that led to satisfaction of these criteria most directly. The accuracy with which this 'calibration' was achieved was quite satisfactory. For states containing more than one kilometre of road, the difference between the predicted and observed length of road in the state averaged 4 per cent of the observed length in the state. The average difference between the predicted length of road work of each type and the reported length was 2.5 per cent. Detailed results are shown in Appendix IV.

While it can be demonstrated that a unique solution was not obtained in each case, there appeared always to be very little latitude in the acceptable numerical values of the elements of the matrix. The transition matrixes from repeated calibrations gave 1991 condition projections which did not significantly differ from each other. Typical results from repeated calibration are also shown in Appendix IV.

LIMITATIONS IMPOSED BY DATA

This study was begun largely because it was known that data comprehensively describing pavement condition were not readily available. As has been discussed, the result was a workable model with some limitations in its theoretical framework.

That framework, and the numerical techniques described in this chapter, anticipated that the readily available data would conform with its inventory specification or otherwise satisfy the purpose for which it was assumed to have been collected. During the course of the study it became clear that such anticipation was not justified. The quality of the available pavement condition and road work data both inhibited the selection of road sets that could be analysed and degraded confidence in the accuracy of the numerical results. This matter is discussed in Appendix II.

The influence of data on the attempted projection of road pavement condition may be summarised in the following way. There is insufficient information available to permit a statistically thorough description of typical pavement behaviour to be developed. If the alternative approach described in this study is adopted, the lack of diversity in the available data precludes a demonstrably unique solution for the model's parameters. Further, inconsistent formats, possible errors and a want of specificity in the data are likely to produce inestimable errors in the values calculated. Therefore, while the numerical results obtained are interesting, they must be regarded as no more than tentative.

CHAPTER 6—APPLICATION TO ROADS IN TASMANIA

ANALYSIS

The Road System

The declared public, sealed, rural arterial roads in Tasmania were examined in three sets, namely:

- State Highways, (Legal Class 1) excluding National Highways
- Main Roads (Legal Class 2)
- Secondary, Development, and Subsidised Roads (Legal Classes, 3, 5 & 6).

The ARS inventory available to BTE covered both arterial and non-arterial, rural and outer urban roads. The NDB inventory for Tasmania covered the rural and outer urban arterials only. Accordingly, BTE analysis was confined to roads which were arterials in 1981. The roads included in each set are listed in Appendix III, and are described briefly in Tables 6.1 and 6.2.

The 1972–81 change in total length of the systems analysed, evident from Tables 6.1 and 6.2, is the result of the construction of new sealed road, and of changes in declarations which moved road from one legal class to another. A fixed set of roads was required for the calculation of deterioration rates and the method of achieving this is described in Appendix III.

Past roadwork

Data on past roadwork were extracted from the annual reports of the Tasmanian Department of Public Works, for the years 1971–72 to 1975–76, and from the annual reports of the Department of Main Roads for subsequent years. The road work done in each year is listed in Tables 6.3 to 6.5 and the average annual rates used for the analysis of pavement condition are listed in Table 6.6. Roadwork is listed for only those roads forming part of the set analysed.

TABLE 6.1—ROAD SYSTEM CHARACTERISTICS; TASMANIA, 1972

	Legal class		
Characteristic	*1*	*2*	*3, 5 & 6*
Length (carriageway km)	1 371.0	682.0	192.0
Per cent of length in			
Functional Class 1	0.4	0.0	0.0
Functional Class 2	66.8	19.8	5.9
Functional Class 3	19.7	67.1	72.5
Functional Class 6	5.1	0.0	0.0
Functional Class 7	3.2	1.5	17.8
Functional Classes 4 & 8	4.9	11.6	3.9
AADT	1 046	765	714

Source: Australian road survey (1969-73, unpublished data).

TABLE 6.2—ROAD SYSTEM CHARACTERISTICS; TASMANIA, 1981

	Legal class		
Characteristic	*1*	*2*	*3, 5, 6*
Length (carriageway km)	1 412.0	720.0	273.0
Per cent of length in			
Functional Class 1	0.0	0.0	0.0
Functional Class 2	65.9	22.3	4.6
Functional Class 3	25.2	75.1	73.2
Functional Class 6	4.4	0.0	0.4
Functional Class 7	4.5	2.6	21.7
Functional Classes 4 & 8	0.0	0.0	0.0
AADT	1 274	926	677

Source: NAASRA data bank sectionised inventory files (1981).

All of the data extraction difficulties described in Chapter 5 and Appendix II were encountered when dealing with Tasmanian data. The most important of these were that:

- The Department of Public Works reports lacked data on bituminous surfacing work ie. initial sealing, resealing and resheeting.
- The length of works reported as extending the seal length did not match the road length differences obtained from comparing the ARS and NDB inventories. For example, the Channel and Huon Highways were both shorter in 1981 than in 1972 despite seal extension roadwork having been carried out in the interim.

General trends in the rates of work are evident from Tables 6.3 to 6.5. In the early years of the decade most of the effort (other than resurfacing works) was directed towards adding to the sealed road network by construction to new seal, particularly on the Highways. From 1975 there was a significant redirection of resources towards repairing existing sealed road stock, through light reconstruction and heavy reconstruction, and towards improving the level of service, by upgrading the width or alignment. Comparison of the average annual work rates (as a percentage of the total length of each legal class) shows a higher rate of reconstruction, upgrading, and new construction on the Legal Class 3, 5 & 6 roads, suggesting that the policy during the decade was to concentrate on the Secondary, Developmental and Subsidised Roads.

Pavement condition

Problems arose in using the ARS inventory data to deduce the condition of roads in Tasmania in 1972. The data for structural condition and surface condition were subjective estimates only and their accuracy and reliability were questionable. The figures recorded may have been biased significantly by consideration of non-engineering factors in the assessment, such as the expected influence of these estimates on likely future road funding. Analysis of the 1972 structural condition data for Tasmanian roads done on a functional class basis indicates that:

- expected remaining pavement service lives for all arterial roads ranged up to 35 years; and
- a large proportion of the roads had a very long remaining service life (60 per cent of rural arterials and 45 per cent of outer urban arterials had estimated remaining lives of over 30 years).

If the maximum remaining service life estimate in the ARS was for a new pavement, that can be taken as the life then expected for most pavements. This gave a value

TABLE 6.3—ANNUAL ROADWORK; LEGAL CLASS 1 ROADS

(km)

Work Type	*1972–73*	*1973–74*	*1974–75*	*1975–76*	*1976–77*	*1977–78*	*1978–79*	*1979–80*	*1980–81*
Resealing	na	na	na	na	70.0	87.4	64.3	99.3	47.8
Resheeting	na	na	na	na	4.5	9.6	5.2	24.4	18.5
Light reconstruction	0	0	15.0	0	12.0	0	12.0	1.5	0.6
Reconstruction	0	0	0	5.0	5.9	25.0	23.7	14.5	16.1
Upgrading									
Widening	0	7.3	4.0	3.0	5.8	8.7	6.4	3.0	2.6
Realignment	0	0	2.5	0	0	0	4.0	3.5	3.2
Extension	35.3	21.3	22.3	7.6	1.3	0	0	0	0

na not available

Source: Annual reports of Tasmanian Department of Main Roads and Department of Public Works.

TABLE 6.4—ANNUAL ROADWORK; LEGAL CLASS 2 ROADS

(km)

Work Type	*1972–73*	*1973–74*	*1974–75*	*1975–76*	*1976–77*	*1977–78*	*1978–79*	*1979–80*	*1980–81*
Resealing	na	na	na	na	25.1	47.0	92.9	55.9	56.2
Resheeting	na	na	na	na	10.2	3.2	6.2	3.7	1.4
Light Reconstruction	0	0	0	0	0	0	0	0	0
Reconstruction	0	0	0	16.9	1.8	6.4	9.3	3.7	0
Upgrading									
Widening	0	0	0	0	0	0	0	0	0
Realignment	0	0	1	2	0	1.4	3.2	0	0
Extension	1.4	5.8	5.9	5.9	0	2	0	0	11.6

na not available

Source: Annual reports of Tasmanian Department of Main Roads and Department of Public Works.

TABLE 6.5—ANNUAL ROADWORK; LEGAL CLASS 3, 5 & 6 ROADS

(km)

Work Type	*1972–73*	*1973–74*	*1974–75*	*1975–76*	*1976–77*	*1977–78*	*1978–79*	*1979–80*	*1980–81*
Resealing	na	na	na	na	12.2	0.3	14.8	2.8	15.7
Resheeting	na	na	na	na	0.4	2.3	4.2	8.2	1.6
Light Reconstruction	0	0	0	0	0	0	0	0	0.2
Reconstruction	0	0	10.0	0	0	3.4	2.9	11.5	8.1
Upgrading									
Widening	0	0	0	0	0	0	2.9	9.2	0
Realignment	0	0	9.0	0	0	4.6	0	0	0
Extension	6.5	10.3	5.5	14.2	5.0	0	0	7.7	2.1

na not available

Source: Annual reports of Tasmanian Department of Main Roads and Department of Public Works.

TABLE 6.6—AVERAGE ANNUAL WORK RATES USED IN DETERIORATION ANALYSIS

(km/year)

	Legal class		
Work Type	*1*	*2*	*3, 5 & 6*
Resealing	73.8	42.1	8.2
Resheeting	12.4	4.2	2.9
Light Reconstruction	4.6	0	0
Reconstruction	10.0	4.2	4.0
Upgrading	6.0	0.7	2.9

of 35 years for road life from construction to reconstruction. The pavement lives that can be derived from the ERVL curves for Tasmania are about 25 years for the Functional Class 1, 2 and 3 roads, 30 years for Functional Class 6 roads, and 39 years for Functional Class 7 roads. These are all in contrast with typical nominal design lives of 20 years for sealed pavements.

Estimation of the 1972 surface condition may also be questioned. Thirty per cent of rural arterials had no remaining seal life left and a reseal was due or overdue. Such an amount seems inordinately high considering that seal life is typically of the order of 10–12 years and that the annual resealing work rate is around 8 per cent of total length.

For alignment assessment, the average highway speed is provided in ARS. This is a weighted average of the design speeds within a section (the weighting is presumably by road length). Safe travel speed is also provided but how this was determined is not specified; most likely it was a single subjective estimate and as such was not the preferred indicator of alignment/speed condition for this study.

For volume/width assessment, there is some doubt about the accuracy of the AADT figures in the rural areas because actual measurements either have not been made or are out of date.

The NDB Sectionised inventory on Tasmanian roads in 1981 provides complete roughness data, nominally taken in that year, for the sealed arterial roads in all of the legal class categories included in this study. However:

- No year of (re)construction data and no PSR data for any roads are present in these three sets.
- Year of (re)seal data are present for Functional Class 1 roads only. There is a Surface Rating for other functional class roads in all but two instances.
- No horizontal curve speed data or vertical curve speed data appears for any roads in the system ie. all alignment/speed data are absent.
- AADT and year of AADT measurement plus forecast AADT are specified for all roads.

All ARS and NDB data were taken at face value and pavement condition was assessed using the methods described in Chapter 5, with the following amplification. The 1972 pavement life used in the analysis of Tasmanian ARS data was, in the first instance, the maximum value of remaining pavement life recorded in the inventory. It was believed that this value would best correspond with the 1972 assessors' views of pavement life, and thus give the best estimate of pavement age in 1972. If this value resulted in a state vector that had so little road in one state that the reported average annual work on that state could not have been done, the pavement life was altered by just the amount necessary to eliminate the discrepancy. The pavement lives used are shown in Table 6.7.

TABLE 6.7—ASSUMED VALUES OF PAVEMENT LIVES FOR CALCULATION OF PAVEMENT AGE IN 1972

(Years)

Functional class	*Legal class* 1 & 2	*Legal class* 3, 5 & 6
1	35	35
2	35	35
3	35	40
6	35	50
7	35	55

With these lives established, the roughness definitions of each condition state were reviewed to ensure broad correspondence with the ERVL pavement age-roughness-tolerability relationships. The roughness definitions used for each structural condition are shown in Table 6.8.

Throughout the analysis the resealing interval was set at 12 years and a sound wearing and sealing course was reckoned to be one less than 9 years old. A road was held to be geometrically inadequate if the volume of traffic was 25 per cent greater than recommended by NAASRA design guides.

Condition state vectors describing Tasmanian roads in 1972 and 1981 are shown in Table 6.9. Note that the change of total road length in each legal class between 1972 and 1981 is evident in these vectors. The sensitivity of the vectors to changes in the pavement life assumed when interpreting the ARS is significant and is described in Appendix IV.

Results

After allowance for changes due to new construction and reclassification between 1972 and 1981, the adjusted state vectors in Table 6.10 were obtained. These vectors were used to obtain the intrinsic deterioration rates and maintenance policies effective between 1972 and 1981. The results are set out in Tables 6.11 to 6.16 which show the *proportions of the length of road in each condition state* that move to other states *in one year.*

Blanks in the tables correspond to inadmissable transitions.

The transition matrices, represented by Tables 6.11 to 6.16, were selected on the basis of their predicting a target vector (the 1981 state vector adjusted by excluding 1972-81 construction and reclassification) from the 1972 state vector. The accuracy

TABLE 6.8—ROUGHNESS DEFINITIONS OF STRUCTURAL CONDITION

(counts/km)

Functional Class	*Condition* *Pi*	*Condition* *Pii*	*Condition* *Piii*
		Legal Classes 1 & 2	
1 & 2	up to 80	80 to 120	above 120
3	up to 110	110 to 150	above 150
6	up to 100	100 to 180	above 180
7	up to 120	120 to 240	above 240
		Legal Classes 3, 5 & 6	
1 & 2	up to 80	80 to 120	above 120
3	up to 100	100 to 120	above 120
6 & 7	up to 120	120 to 180	above 180

with which this prediction was achieved, while also predicting the 1972–81 annual average work rates, is shown in Appendix IV.

TABLE 6.9—PAVEMENT CONDITION STATE VECTORS; 1972 AND 1981
(carriageway km)

	Condition state number							
Road type	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Legal Class 1 roads								
1972	447	376	147	250	0	4	2	145
1981	323	200	381	217	14	177	3	97
Legal Class 2 roads								
1972	165	428	11	52	0	1	0	25
1981	368	216	70	44	0	21	0	1
Legal Class 3, 5 & 6 roads								
1972	30	119	19	14	0	2	0	7
1981	145	41	43	12	1	24	0	7

TABLE 6.10—PAVEMENT CONDITION STATE VECTORS; 1972 AND 1981, ADJUSTED FOR RATE DERIVATION PURPOSES
(carriageway km)

	Condition state number							
Road type	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Legal Class 1 roads								
1972	447	367	147	250	0	4	2	145
1981	272	203	385	219	14	179	3	97
Legal Class 2 roads								
1972	165	428	11	52	0	1	0	25
1981	330	216	70	45	0	21	0	1
Legal Class 3, 5 & 6 roads								
1972	30	119	19	14	0	2	0	7
1981	64	41	43	12	1	24	0	7

TABLE 6.11—INTRINSIC DETERIORATION RATES; LEGAL CLASS 1 ROADS
Proportion of road changing condition each year
(per cent)

	To condition				
From condition	*Siii Pi*	*Si Pii*	*Siii Pii*	*Si Piii*	*Siii Piii*
Si Pi	6.0	15.5	1.2		
Siii Pi			15.6		
Si Pii			7.0	7.8	0.9
Siii Pii					12.8
Si Piii Gi					27.5
Si Piii Giii					24.4

Note: Blanks correspond to inadmissable transitions.

IMPLICATIONS

Maintenance Policy

When reviewing the deduced maintenance policies presented in Tables 6.14 to 6.16, one should be aware that the length of road in the Siii Piii Gi condition (state 7) has been very small. The high probabilities caiculated for work being done on these roads are therefore not necessarily significant.

The significant differences between the three maintenance policies described are:

- the extent to which bituminous resheeting or heavy resealing appears to have

TABLE 6.12—INTRINSIC DETERIORATION RATES; LEGAL CLASS 2 ROADS

Proportion of road changing condition each year (per cent)

From condition	*To condition* Siii Pi	Si Pii	Siii Pii	Si Piii	Siii Piii
Si Pi	6.2	3.2	0.6		
Siii Pi			13.4		
Si Pii			10.8	10.5	0.4
Siii Pii					15.0
Si Piii Gi					35.0
Si Piii Giii					17.5

Note: Blanks correspond to inadmissable transitions.

TABLE 6.13—INTRINSIC DETERIORATION RATES; LEGAL CLASS 3, 5, & 6 ROADS

Proportion of road changing condition each year (per cent)

From condition	*To condition* Siii Pi	Si Pii	Siii Pii	Si Piii	Siii Piii
Si Pi	3.3	16.7	0.7		
Siii Pi			13.3		
Si Pii			3.6	21.7	5.0
Siii Pii					28.5
Si Piii Gi					43.6
Si Piii Giii					30.0

Note: Blanks correspond to inadmissable transitions.

TABLE 6.14—DERIVED MAINTENANCE POLICY; LEGAL CLASS 1 ROADS

Proportion of road changing condition each year (per cent)

From condition	*To condition* Si Pi	Si Pii	Si Piii
Siii Pi	15.6		
Siii Pii	2.0	8.2	
Siii Piii Gi	0.1	0.3	0.3
Siii Piii Giii	18.7	0.3	29.0

Note: Blanks correspond to inadmissable transitions.

been used to defer reconstruction on Legal Class 1 roads, as evidenced in the Siii Piii to Si Piii transition; and

- the relatively high probability that Legal Class 2, 3, 5 and 6 roads would be upgraded if they required it.

The structural effects of upgrading are masked in the State road authority's reports and may have been overestimated in this analysis.

Deterioration

Care is necessary when comparing the deduced intrinsic deterioration rates of roads in the different legal classes. The physical condition of Legal Class 1 and 2 roads in the Si Pii state, for example, is different from that of Legal Class 3 roads in the Si Pii state. Nevertheless, the values in Tables 6.14 to 6.16 do suggest that the initial structural deterioration of Legal Class 2 road is taking place more slowly than for roads in the other two legal classes. Deterioration to a condition requiring reconstruction appears to be taking place most quickly in Legal Class 3, 5 and 6 roads. Such a result might be explained by there being lighter traffic, vis a vis pavement strength, on Legal Class 2 roads.

This prompts further consideration of the question of pavement life. One of the techniques of Markov chain analysis is the calculation of 'mean first passage time', meaning in this case the average time taken for a road to proceed from one state to another, given all the possible state to state paths. For roads, the mean first passage times are dictated not only by the intrinsic deterioration rates, but also by the work done which has the effect of delaying deterioration.

'Pavement life' is an ill-defined term. More explicit terms would be 'life till reconstruction required' or 'life till reconstruction commences'. Those terms themselves require qualification, because the life will vary with the maintenance policy adopted. Mean first passage times taken from the transition matrices derived for

TABLE 6.15—DERIVED MAINTENANCE POLICY; LEGAL CLASS 2 ROADS

Proportion of road changing condition each year
(per cent)

From condition	*To condition* *Si Pi*	*Si Pii*	*Si Piii*
Siii Pi	13.4		
Siii Pii	0.0	13.7	
Siii Piii Gi	65.0	0.0	35.0
Siii Piii Giii	95.0	0.0	5.0

Note: Blanks correspond to inadmissable transitions.

TABLE 6.16—DERIVED MAINTENANCE POLICY; LEGAL CLASS 3, 5 & 6 ROADS

Proportion of road changing condition each year
(per cent)

From condition	*To condition* *Si Pi*	*Si Pii*	*Si Piii*
Siii Pi	10.4		
Siii Pii	0.0	23.9	
Siii Piii Gi	80.0	0.0	0.1
Siii Piii Giii	99.1	0.0	0.9

Note: Blanks correspond to inadmissable transitions.

Tasmanian roads[1] gave the mean pavement lives listed in Table 6.17. The calculated standard deviations of the pavement lives were between 55 per cent and 75 per cent of the mean.

It must be emphasised that there is no need for correspondence between these lives and the pavement life assumed in this study when interpreting ARS data. The latter is an estimate of what the 1972 assessor thought pavement life would be, and not necessarily an estimate of the true life.

Projected condition

Three projections of pavement condition were made for each set of roads analysed. Each projection ran ten years forward from 1981.

The first assumed retention of the current maintenance policy. To illustrate the effectiveness of this policy, the second assumed that no road work would be done. The third projection used a maintenance policy intended to hold overall pavement condition in approximately the 1981 state, and in particular to prevent an increase in the length of road in the SP condition. No allowance was made in these projections for new construction after 1981. Nor was any attempt made to ensure that the assumed maintenance policies were practical in detail. The results are shown in Tables 6.18, 6.20 and 6.22 which also include the 1972 and 1981 condition for comparison. The road work which each of these projections entailed is shown in Tables 6.19, 6.21

TABLE 6.17—DERIVED MEAN PAVEMENT LIVES

(Years)

	Life till reconstruction required		*Life till reconstruction commences*
Road type	*In absence of maintenance*	*With current maintenance policy*	*With current maintenance policy*
Legal Class 1	17	28	40
Legal Class 2	13	69	71
Legal Class 3, 5 & 6	12	15	16

TABLE 6.18—PAST AND PROJECTED PAVEMENT CONDITION; LEGAL CLASS 1 ROADS

(carriageway km)

	Condition state					
	Si Pi	*Siii Pi*	*Si Pii*	*Siii Pii*	*Si Piii*	*Siii Piii*
Past condition						
1972 (from ARS)	447	376	147	250	4	147
1981 (from NDB)[a]	323	200	381	217	191	100
1991 projections						
At past maintenance policy	238	118	377	232	282	161
At zero roadwork	24	66	143	275	78	821
At holding maintenance policy	278	129	414	269	212	106

a. Includes effects of new construction.

1. For the transitions from state 1 to state 8 to state 1.

and 6.23, as calculated under the assumptions of 'maintenance efficiency' and work distribution between condition states outlined in Chapter 4.

This analysis reveals that, for Tasmanian sealed rural arterials as a whole, the proportion requiring reconstruction (ie in the Siii Piii condition) is projected to rise, under current maintenance policies, from 5 per cent of system length in 1981 to 8.5 per cent in 1991. In addition, the proportion of road so rough as to require reconstruction, but with sound wearing and sealing course, would rise by 130km under this projection to 17 per cent of system length. During this period, the annual rate of reconstruction is projected to rise from the past 28 km/year to some 44 km/year.

To hold the length of road requiring reconstruction near static at the 1981 value would require the rate of reconstruction to be increased by 28 km/year to 56 km/year, and the rate of light reconstruction to increase from a present 4.7 km/year to 14 km/year.

In each of these projections the rate of resealing would fall commensurately with reconstruction rate increases.

TABLE 6.19—PAST AND PROJECTED ROADWORK 1972-91; LEGAL CLASS 1 ROADS

(km)

	Resealing	*Light reconstruction*	*Bituminous resheeting*	*Reconstruction*[a]
Past work				
1972 to 1981 (from SRA records)	738	46	124	160
1982-91 projections				
At past maintenance policy	428	47	374	238
At holding maintenance policy	353	64	255	369

a. Includes reconstruction associated with geometric improvements.

TABLE 6.20—PAST AND PROJECTED PAVEMENT CONDITION; LEGAL CLASS 2 ROADS

(carriageway km)

	Condition state					
	Si Pi	*Siii Pi*	*Si Pii*	*Siii Pii*	*Si Piii*	*Siii Piii*
Past condition						
1972 (from ARS)	165	428	11	52	1	26
1981 (from NDB)[a]	368	216	70	45	21	1
1991 projection						
At current maintenance policy	337	173	87	66	44	9
At zero roadwork	128	125	32	162	23	249
At holding maintenance policy	345	175	76	79	36	9

a. Includes effects of new construction.

TABLE 6.21—PAST AND PROJECTED ROADWORK 1972-91; LEGAL CLASS 2 ROADS

(km)

	Resealing	*Light reconstruction*	*Bituminous resheeting*	*Reconstruction*[a]
Past work				
1972 to 1981 (from SRA records)	421	0	42	50
1982-91 projections				
At past maintenance policy	276	0	68	60
At holding maintenance policy	241	38	35	64

a. Includes reconstruction associated with geometric improvements.

TABLE 6.22—PAST AND PROJECTED PAVEMENT CONDITION; LEGAL CLASS 3, 5 & 6 ROADS

(carriageway km)

	Condition state					
	Si Pi	*Siii Pi*	*Si Pii*	*Siii Pii*	*Si Piii*	*Siii Piii*
Past condition						
1972 (from ARS)	30	119	19	14	2	7
1981 (from NDB)[a]	145	41	43	12	26	7
1991 projections						
At past maintenance policy	98	29	65	14	46	18
At zero roadwork	14	19	19	17	23	179
At holding maintenance policy	108	31	60	13	45	15

a. Includes effects of new construction.

TABLE 6.23—PAST AND PROJECTED ROADWORK 1972-91; LEGAL CLASS 3, 5 & 6 ROADS

(km)

	Resealing	*Light reconstruction*	*Bituminous resheeting*	*Reconstruction*[a]
Past work				
1972 to 1981 (from SRA records)	82	0	29	69
1982-91 projections				
At past maintenance policy	39	0	31	140
At holding maintenance policy	39	38	0	127

a. Includes reconstruction associated with geometric improvements.

CHAPTER 7—APPLICATION TO ROADS IN VICTORIA

ANALYSIS

The Road System

In Victoria the road condition model was applied to one set of roads only, namely all sealed State Highways, including national highways, declared under the Country Roads Act, for all Country Roads Board (CRB)[1] administrative divisions other than the Metropolitan and Dandenong divisions.

The proposal had been to examine the sealed rural arterial component of each declared legal class (with the exclusion of national highways) ie Freeways, State Highways, Tourists' roads, Forest roads and Main roads. These were to be modelled separately or aggregated into suitable sets. These roads appeared in both the 1972 ARS and 1981 NDB data files, and consistent sets of roads could be identified and described for the two points in time. However, serious shortcomings in the actual data available precluded derivation of condition vectors for much of the Victorian road network.

Firstly, the inventories available to describe the road condition in 1981 were deficient in one major respect. For all legal classifications other than Freeways and Highways, no seal condition data (ie year of reseal or surface rating) were reported at all. This restricted the feasible analysis to Freeways and Highways. (A similar situation encountered in NSW data completely precluded analysis of NSW roads).

Secondly, the available description of the roadwork done by CRB was such as to prevent distinctions being drawn between road types on the basis of:

- local or arterial function;
- urban or rural area; and
- national highway or other highway declaration.

This left a choice to be made from the following three analysable sets of roads each with its own component of uncertainty and error.

State Highways plus Freeways, for the whole State except the urban areas. Errors in this instance would have arisen from not being able to separate the roadwork that was performed on urban roads from that performed on rural and outer urban roads.

State Highways only, for the whole State except urban areas. This choice would have reduced the error due to roadwork done on the urban roads (where most of the freeways lie) but there would have been an increase in the error due to changes in the road system length caused by changes in declaration of Highway to Freeway.

State Highways only, for the whole State except the Metropolitan and Dandenong Divisions which cover the Melbourne urban area. The error here due to work done on the remaining urban areas in the provincial cities would be much smaller than in the previous set, whereas the error arising from changes in length declarations would be greater.

1. The Country Roads Board was disbanded and the Road Construction Authority was formed on 1 July 1983.

It was considered that the reduction of the error in roadworks measurement was more significant than the increase in error due to variations in the road system so the last of the three sets was selected for analysis. Because of the aggregated nature of the data, it was not possible to minimise the errors caused by variation in the road system's composition as was done for the Tasmanian roads sets, where adjustment was done on a road-by-road basis.

The roads included in the set of State Highways are listed in Appendix III. Table 7.1 describes some salient characteristics of the 1972 and 1981 rural State Highways.

Past roadwork

Data on past roadwork were extracted from the annual reports of the CRB for the years 1972–73 to 1980–81 inclusive. The annual reports contain lists of significant works carried out by the Works Sub-branch; these indicate the location of the work by road name and local government area name, the type of work performed using some brief description (eg duplication, extension of seal, reconstruction) and the extent of the work in either route-kilometres or carriageway-kilometres. The reports also contain summary tables produced by the Asphalt Division. These show the bituminous surfacing work carried out on each road legal class to which the CRB contributed funds. The bituminous surfacing work is categorised as either sprayed work or plant mixed work and is further classified as either initial treatment or re-treatment. Initial treatment includes extension of sealed system, reconstruction of existing seal, widening of existing seal, duplicating of existing seal and final seal.

As stated earlier, the data are deficient in several respects. The list of significant works cannot be utilised as the measure of roadwork performance because it is only a selective and unrepresentative sample of all the works actually carried out. The term 'significant' nominally denotes that the project costs were greater than $100,000 (so no light reconstruction is given) and the published list serves merely to indicate generally what each division did during the year.

This analysis was therefore necessarily based on using aggregate bituminous surfacing summary tabulations to measure the level of roadworks carried out over the period being studied. Recourse was made to the list of significant works only in order to ascertain the proportion of reconstruction of sealed pavement done on the existing alignment and that done on substantially new alignment.

Further summary data were obtained from the CRB listing the length of bituminous sprayed seal work done on State Highways in the Metropolitan and Dandenong divisions so that these two divisions could be subtracted from the overall State figures

TABLE 7.1—VICTORIAN STATE HIGHWAY SYSTEM CHARACTERISTICS; RURAL DIVISIONS

Characteristics	*1972*	*1981*
Total length (Carriageway km)	6 641.0	6 581.0
Sealed length	6 389.0	6 302.0
Length in class (per cent)		
Functional Class 1	14.1	12.7
Functional Class 2	55.0	48.5
Functional Class 3	29.8	37.5
Functional Class 6	1.0	0.6
Functional Class 7	0.2	0.2
Functional Class 4 & 8	0.0	0.5
AADT[a]	1 506	1 774

a. Length-weighted average.

to produce work rates for what are referred to hereafter after as the rural divisions. Such data were not available for plant mixed work on a divisional basis and this small length of work was proportionally allocated as explained in Appendix III.

The annual roadwork calculated to have been done on State Highways in the eight rural divisions is given in Table 7.2. The average annual work rates used in the deterioration analysis are given in the last column of Table 7.2.

Pavement condition data

The ARS inventory was used to determine the condition of State highways in Victoria in 1972 in the manner described previously for Tasmania. The verisimilitude of this data may be deceptive since:

- the structural condition data are subjective estimates of remaining pavement life;
- the surface condition data are subjective estimates of remaining seal life; and
- the AADT figures in the rural areas are of questionable accuracy, often being deduced by extrapolation from limited traffic survey data.

The NDB inventory of Victorian roads in 1981 describes almost all declared rural and outer urban roads, both local and arterial, including national highways. Table 7.3 indicates how thoroughly this inventory describes road condition in Victoria. The classifications used in the table are:

Legal Class 1—Freeways
Legal Class 2—Highways
Legal Class 3—Forest Roads
Legal Class 4—Tourist Roads
Legal Class 5—Main Roads

The classification is a coding convention used in Victoria and is not necessarily embodied in legislation.

Structural condition

To determine 1972 structural condition from the remaining service life recorded in the ARS, a value was required for the pavement life used by the 1972 assessors.

Analysis of the ARS structural condition data item revealed that the maximum expected remaining service life was 30 years; this applies across all legal and functional class categories. The cut-off value is quite sharp, suggesting that this was a standard assessment criterion employed by the assessors to define a service life.

Calculations based on the ERVL study of the mean pavement age equivalent to the effective average roughness at reconstruction gave the following values of mean pavement life.

Functional Class 1—32.1 years
Functional Class 2—30.3 years
Functional Class 3—25.0 years
Functional Class 6—32.5 years
Functional Class 7—33.9 years

The reciprocal of the mean rate of reconstruction per annum of sealed pavements is the mean pavement renewal interval. Over the past decade, Victorian State Highways have been reconstructed or upgraded at a rate of about 2.6 per cent per annum, implying an interval of around 38 years.

A pavement life of 30 years was used in interpreting ARS data to obtain 1972 structural condition. The significant influence of pavement life assumptions on the 1972 state vector is shown in Table 7.4.

TABLE 7.2—ANNUAL ROADWORK ON STATE HIGHWAYS; RURAL DIVISIONS 1972-81

(carriageway-km)

Work type	*1972–73*	*1973–74*	*1974–75*	*1975–76*	*1976–77*	*1977–78*	*1978–79*	*1979–80*	*1980–81*	*Total*	*Average*
Resealing	544.47	575.17	500.75	695.12	683.56	507.20	567.70	643.28	617.50	5 396.75	599.0
Resheeting	3.05	3.26	5.83	3.67	11.36	9.86	3.60	6.32	1.51	48.46	5.4
Light reconstruction	na	na	na	na	na	na	na	na	na	na	na
Reconstruction	97.03	93.40	85.42	64.23	53.65	63.70	43.79	62.01	37.84	601.07	66.8
Upgrading											
Widening	50.68	46.88	52.71	32.56	47.48	61.31	61.79	81.70	75.50	510.61)	
Alignment	84.38	81.21	74.27	55.86	46.66	55.39	38.08	53.95	32.90	522.68)	115.0
Construction											
Duplication	28.58	5.31	34.44	17.01	18.19	22.02	17.19	16.66	7.43	166.83)	
Extension	4.02	2.09	.90	1.10	0.00	0.60	0.00	0.88	1.20	10.79)	19.7

na not available

Source: Estimate based on Victorian Country Roads Board data.

TABLE 7.3—PROVISION OF CONDITION DATA IN NDB INVENTORY; 1981

Data type	Road Legal Class 1	2	3	4	5
Total no of records[a]	277	6 920	68	109	2 003
No of records giving roughness	216	6 551	16	62	1 067
PSR	277	6 920	68	109	1 998
Year of (re)construction	40	5 699	0	0	0
Year of (re)seal	221	6 507	0	0	0
Surface Rating	0	0	0	0	0
AADT	277	6 920	68	109	2 003

a. The NDB uses about one computer record per km of road.

TABLE 7.4—CONDITION STATE VECTORS UNDER VARIOUS PAVEMENT LIFE VALUES 1972
(carriageway/km)

Assumed pavement life	Condition state number 1	2	3	4	5	6	7	8
30 years	3862	569	642	752	120	69	199	175
32 years	3322	279	813	815	375	202	356	246

Structural condition in 1981 was obtained by using roughness data from the NDB where available. Otherwise the roughness value was obtained from PSR using a function provided by the CRB, viz.

$$R = 219 - 42 * PSR$$

where: R is roughness (in counts/km)
PSR is Present Serviceability Rating (five point scale)

Roughness is also calculable from pavement age using the ERVL functions, though it was not necessary to resort to such a calculation because the PSR data was complete.

The roughness values characterising each condition state were initially set, on the basis of the Tasmanian analysis and advice from the CRB, to values which were expected to typify CRB past practice. It became clear from the resulting state vectors that these roughness values were inconsistent with the length of road that the CRB had reconstructed after 1978. The inconsistency was not evident in the 1972 state vector.

Accordingly, the roughness definitions of the condition states were adjusted for 1981, by the smallest amount necessary to remove the inconsistency. The values adopted are shown in Table 7.5.

The implication of using 1981 state definitions different from those in 1972 is that the CRB, over a ten year period, changed its conception of the roughness at which pavement 'required' reconstruction. This example serves to illustrate the way in which varying standards for quality may be reflected in the type of analysis used in this study.

Whether or not this change actually occured is disputable. There is, however, a difference between reported pavement condition and road work rates of 1972 and those of 1981 which is not simply explicable.

Wearing and sealing course condition

Seal age was again used as a proxy for seal condition. Seal age in 1981 was available directly from the NDB. To determine seal age from the 1972 ARS it was necessary to subtract the recorded remaining seal life from a notional resealing interval.

1972 ARS estimates of remaining seal life were up to 12 years for bituminous concrete and up to 8 years for simple bituminous seal. A notional resealing interval of 12

TABLE 7.5—ROUGHNESS DEFINITIONS OF CONDITION STATES
(counts/km)

Road functional class	*Condition*		
	Pi	*Pii*	*Piii*
		1972 state vector	
1	up to 80	80–120	more than 120
2	80	80–120	120
3	100	100–120	120
6	120	120–180	180
7	120	120–180	180
		1981 state vector	
1	up to 70	70–95	more than 95
2	70	70–95	95
3	70	70–95	95
6	120	120–150	150
7	120	120–150	150

years was assumed and the condition of the seal was initially assumed to be satisfactory for a further 8 years (ie seals greater than 8 years old were deemed to be in a state warranting restoration). This is roughly commensurate with the resealing rate of 9.5 per cent per annum between 1972 and 1981.

This analysis was refined by the choice of a seal age to define each condition state. The choice was made by comparing the vectors generated with the reported work rates and selecting the seal life which gave the best agreement between the initial assumptions, the length requiring resurfacing, and the amount of resealing plus resheeting actually performed. A value of 9 years to define Siii gave insufficient length of roads needing resurfacing to permit the amount of reported work to be done, whereas a value of 8 years enabled this inequality to be satisfied.

Results

The raw condition state vectors, unadjusted for changes in length, describing Victoria's rural State highway system in 1972 and 1981 are shown in Table 7.6. After correction for new construction and for changes through reclassification, net state vectors were obtained and these are shown in Table 7.7. From this pair of vectors the intrinsic deterioration rates and the effective maintenance policy over the 1972–81 period were found; these are set out in Tables 7.8 and 7.9 respectively. These tables show the proportions of the length of road in each condition state that make a transition out of that state to other states in one year i.e. in one step-period of the Markov chain.

The transition matrix, which Tables 7.8 and 7.9 represent, was selected on the basis of its predicting a target vector, namely the 1981 state vector corrected for new construction and reclassification occurring between 1972 and 1981, together with the reported average annual work rate for 1972–81, from the 1972 state vector. The accuracy achieved is shown in Appendix IV.

IMPLICATIONS

Several of the intrinsic deterioration rates in Table 7.8 appear to be quite high. For example, about 38 per cent of structurally satisfactory road requiring reseal will deteriorate within one year to a condition requiring light structural work. And, about 38 per cent of road requiring both light structural work and resealing will deteriorate in one year to require reconstruction. There seems to be no method of corroborating these percentages short of some future physical survey. The corresponding deterioration rates for similarly classified Tasmanian roads were about 14 per cent per year. Some of the difference might be explained by the extra traffic on the Victorian roads (see Tables 7.1 and 6.1), however, the validity of any direct comparison is questionable, because, despite the partial numerical definition of the condition states, condition is still fundamentally defined in terms of work perceived by the SRA to be required.

To illustrate, the annual probability of deterioration from the Si Piii Gi condition to an Siii Piii condition is 27.5 per cent on Tasmanian State Highways but 44.6 per cent in Victoria (Tables 6.11 and 7.8). The simplest interpretation of this disparity is not that Victorian seal is less durable, but that the *average* seal age for Si Piii Gi roads is greater in Victoria than in Tasmania. This would be the consequence of a Tasmanian policy of resealing Siii Piii roads that the Victorian road authority would have reconstructed.

Maintenance policy comparisons can be made more directly. From Table 7.9 and Tables 6.14 to 6.16 it can be seen that, for those roads in each State thought to require reconstruction, a greater proportion is repaired annually in Victoria than in Tasmania. Table 7.9 also indicates that while Victorian State Highways requiring reconstruction are almost always repaired as soon as they reach that condition, those with inadequate geometry are significantly more likely to be reconstructed.

TABLE 7.6—PAVEMENT CONDITION VECTORS FOR VICTORIAN STATE HIGHWAYS

(carriageway.km)

	Condition state							
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1972	3278	1153	444	951	13	81	118	352
1981	3421	1123	976	240	188	198	56	99

TABLE 7.7—PAVEMENT CONDITION VECTORS FOR VICTORIAN STATE HIGHWAYS; ADJUSTED FOR RATE DERIVATION PURPOSES

(carriageway.km)

	Condition state							
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1972	3278	1153	444	951	13	81	118	352
1981	3380	1171	994	279	188	202	61	113

TABLE 7.8—INTRINSIC DETERIORATION RATES; VICTORIAN STATE HIGHWAYS

Proportion of road changing condition each year (per cent)

From condition	*To condition*				
	Siii Pi	*Si Pii*	*Siii Pii*	*Si Piii*	*Siii Piii*
Si Pi	13.30	4.09	0.65		
Siii Pi			37.75		
Si Pii			8.35	12.75	3.10
Siii Pii					38.09
Si Piii Gi					44.60
Si Piii Giii					66.00

Note: Blanks correspond to inadmissable transitions.

TABLE 7.9—DERIVED MAINTENANCE POLICY; VICTORIAN STATE HIGHWAYS

Proportion of road changing condition each year (per cent)

From condition	*To condition*		
	Si Pi	*Si Pii*	*Si Piii*
Siii Pi	37.74		
Siii Pii	0.00	33.19	
Siii Piii Gi	88.80	0.00	11.10
Siii Piii Giii	99.00	0.00	0.00

Note: Blanks correspond to inadmissable transitions.

Calculation of the Markov chain's mean first passage times indicated that the average time elapsed between successive reconstruction of a road under the current maintenance policy is 59 years for Victorian State Highways (with a standard deviation of 50 years.) Similar values were obtained for main roads in Tasmania.

This is a remarkable result given the general belief that the life of a pavement is typically some 35 years. Setting aside questions of data accuracy, the following comments are made.

The 35 year life may have had its origins in observations of the reconstruction rates over periods some 10 years in length, during which these rates averaged some 3 per cent of the system length per year. Because the time between failures in a system of roads is not a good measure of the time between failures of a single road, and because time between repairs is not a good measure of time between failures, this procedure may well have underestimated road life. More direct assessments of life to reconstruction would inevitably have used truncated data. That is, the set of roads used for life estimation would not have included the more durable roads which had not, at the date of the assessment, yet been reconstructed. This would also result in an underestimation of pavement life. If the standard deviation of 50 years is correct, both of these life estimation techniques could be expected to have large error, especially when applied to an immature road system. By examining the full life cycle of pavements, the Markov chain analysis may have given a more realistic estimate of pavement life.

An alternative explanation is that, in examining post-reconstruction behaviour, the analysis in this Paper dealt only with roads reconstructed after 1972. The apparent additional 24 years of life may then have resulted either from a higher structural quality of recent reconstruction, or from preventative maintenance practices different from those in force say 20 years earlier.

Either of these explanations leaves the conclusion that, under present circumstances, mean 'pavement life' appears to be about 60 years. However, this mean is associated with a large standard deviation.

Projections

Two projections of pavement condition were made for Victorian rural State Highways. Each projection ran ten years forward from 1981. The first assumed retention of the maintenance policy observed from 1972 to 1981. The second assumed that no road work would be done after 1981, so as to demonstrate the effectiveness of the present policy. The results are shown in Table 7.10 and 7.11.

One of the properties of many Markov chain processes is that, if allowed to run long enough, they will reach an equilibrium in which the state vector does not change from year to year. The equilibrium state vector is a unique property of the particular transition matrix. It follows that for any state vector there is perhaps a transition matrix which makes the vector an equilibrium state vector. Such a matrix might be obtained by adjusting the matrix elements which describe maintenance policy. The resulting maintenance policy would then be one which held the road system in its current overall condition.

In the analysis of Victorian State Highways, the transition matrix derived as the average effective from 1972 to 1981, when used to project forward from 1981, gave an equilibrium state vector by 1984. In short, the current past average maintenance policy will hold Victorian State Highways in close to their 1981 condition.

This policy would entail future annual rates of road work equal to about 90 per cent of the 1972-1981 averages.

TABLE 7.10—PAST AND PROJECTED PAVEMENT CONDITION; VICTORIAN STATE HIGHWAYS
(carriageway.km)

	Condition state					
	Si Pi	*Siii Pi*	*Si Pii*	*Siii Pii*	*Si Piii*	*Siii Piii*
Past condition						
1972 (from ARS)	3 278	1 153	444	951	92	470
1981 (from NDB)[a]	3 421	1 123	976	240	386	155
1991 projections						
Past maintenance policy	3 375	1 188	932	262	372	168
Zero maintenance	467	305	229	592	156	4 547

a. Includes effects of new construction and reclassification 1972 to 1981.

TABLE 7.11—PAST AND PROJECTED ROAD WORK 1972-91; VICTORIAN STATE HIGHWAYS
(carriageway.km)

	Work types			
	Resealing	*Light reconstruction*	*Bituminous resheet*	*Reconstruction*[a]
Past work				
1972-81 (records)	5994	0	54	1815
1981-91 projection				
Past maintenance policy	5320	0	33	1621

a. Includes reconstruction associated with geometric improvement.

CHAPTER 8—CONCLUDING REMARKS

Adopting the premise that road pavement behaviour is statistically predictable, this study was begun with three propositions.

Firstly, that, when viewed as single entities, road networks appear to change condition at a low, near constant rate and that there is no alternative but to treat them as though they are equilibrium systems.

Secondly, that the maintenance policies in force have been those of repair according to condition. This implies a near constant failure rate over time both for chance failures, and for wear-out failures in an equilibrium system.

Thirdly, that any current rate of change of pavement condition is better represented by present condition rather than by pavement age.

These propositions lead to the conclusion that, *for road in a given condition, the probability of changing condition in one year is constant over time,* and invite the application of a Markov chain analysis with states defined by pavement condition. The validity of the conclusion has not been experimentally verified. The Markov chain analysis adopted was one which took the coarsest tolerable approach to the study objectives, so as to minimise data requirements.

In order to link roadwork and deterioration protocols within a single transition matrix, *pavement condition was defined by the type of work required to restore the pavements.* This was also believed to increase the reliability of the assumption of constant probabilities of transition.

The conclusion drawn from this study is that, subject to some theoretical reservations common to most reliability analyses, the Markov chain is a useful technique for maintenance analysis in the presence of multiple failure modes and repair types, and where wear-out is significant. This is especially so if the condition states are classified according to the work required to restore serviceability.

The technique is, then, one to be considered when 'on-condition' maintenance philosophy prevails. That is, inter alia, in circumstances where in-service determination of condition is possible before the subject items become irreparable. The technique cannot be used, however, to deal with condition states which were not permitted to exist in the past.

The principal difficulty experienced in using this type of analysis was that of capturing past maintenance policies and past deterioration rates to provide numerical values for the transition matrix. This difficulty resulted from the structure and quality of the inventory of the 1972 Australian Road Survey and the SRA records used for the purpose.

Despite the uncertainties of both theory and data, it did prove possible to derive a transition matrix which would predict the pavement condition observed in 1981 from that observed in 1972, together with the accumulated roadwork. The matrices derived were not unique solutions but, within the range of likely solutions, the resulting projection of pavement condition in 1991 was sensibly constant.

The numerical results of the study tend to confirm suspicions that increased emphasis will need to be placed on restoring the structural strength of some Australian rural road pavements if rural pavement condition is to be held in its present overall state.

Specifically, but with less confidence, the study results suggested that the annual rate of road reconstruction in Tasmania would need to be doubled for that purpose. On the other hand, reconstruction at the 1972–1981 average rate was projected to hold Victorian State Highways in their present condition.

Application of the method in this study entrained additional assumptions which were more seriously questionable than those of the basic theory. Nevertheless, when viewed pragmatically, in the light of the current knowledge of pavement behaviour, both the method and the numerical results appear to be a useful contribution to the strategic planning of roadworks.

The questionable assumptions were imposed by the will-o'-the-wisp character of available historical records of roadwork and pavement condition. This happened despite the fact that the analytical method was designed to use low quality data.

While there is scope for further work, in refining and amplifying this study, it is clear that further numerical work will be hampered by data deficiencies of the type already experienced. Indeed, it might be said that the numerical basis for the national strategic planning of roadworks will remain inadequate while current data collection policies are in force. This method, and its promise for the future, do provide a basis for data collections of more direct relevance and greater practicability.

APPENDIX I—ALGEBRAIC ANALYSIS

This appendix outlines the algebraic used in the derivation of an approximate transition matrix. The objective of the analysis was to obtain an isomorph to the transition matrix of any road system by finding expressions for the matrix elements that correspond to any given change in state vector and any given amounts of roadwork in one step of the Markov chain.

The transition matrix was eventually to be decomposed into two sets of numbers:

- the transition frequencies due to road work; and
- the transition frequencies resulting from deterioration in the absence of maintenance (the 'intrinsic deterioration rates')

This was to permit alternative transition matrices to be assembled, for subsequent projection purposes, using the intrinsic deterioration rates as a characteristic of the road system, and revised work transition frequencies to represent changed maintenance policy. The algebraic analysis was intended to support this decomposition.

DATA AND NOTATION

The analysis was conducted on the basis that the following information would be known.

- the recorded length of resealing during the period, represented by Ar;
- the length of light reconstruction during the period, represented by B;
- the recorded length of bitumen resheeting during the period, represented by Cr;
- the length of reconstruction during the period, represented by D;
- the length of upgrading during the period, represented by E; and
- the length of road in each condition state at the beginning of the period, represented by N1 to N8, and at the end of the period, represented by N1' to N8'.

Of the possible transitions, only those admitted in Chapter 4 were considered and these were denoted, for example, by T12—meaning the proportion of the length of road in state 1 that moved to state 2 in one period.

For identification purposes, transitions due to roadwork were given the designation W, where Wij is synonymous with Tij.

ROAD WORK

Expressions for the work transitions Wij were obtained in the following way.

Of the recorded resealing for the period denote the quantity done on roads in state 2 by A and on other roads as γAr, then:

(1) $A = Ar - \gamma Ar$

The resurfacing work done on roads outside state 2 is then:

(2) $C = Cr + \gamma Ar$

As it was quite apparent that there would be too few *a priori* relationships available to give a solution for all transition frequencies, the less important work rates were re-expressed in terms of arbitrary constants to be evaluated by other means.

The probability of resurfacing roads in state 7 was taken to be a constant εtimes the probability of reconstructing them and thus:

(3) $W75=\varepsilon W71$

A similar argument was applied to roads in state 8 to give:

(4) $W86=\eta W81$

The probability of doing light reconstruction on roads in state 8 was held to be the same as for roads in state 7 (that is, independent of geometric condition) and equal to a constant times the reconstruction rate. Thus:

(5) $W75=W83=\zeta W81$

Reconstruction was held to be distributed between roads in state 8 and state 7 in the ratio of the lengths of road in those states (after the length of upgrading was removed from state 8) weighted by a factor κ.

Allocating the various types of work to transitions as in Chapter 4 gives:

Resealing

(6) $W21\ N2=A$

Light Construction

(7) $W41N4+W73\ N7+W83\ N8=B$

Resurfacing outside state 2

(8) $W43N4+W75\ N7+W86\ N8=C$

Reconstruction on state 7

(9) $W71\ N7=D-\kappa D\ (N8-E)/(N7+N8-E)$

Upgrading and Reconstruction on state 8

(10) $W81\ N8=E+\kappa D\ (N8-E)/(N7+N8-E)$

Re-arrangement of equations 1 to 8 gives the individual work transition frequencies in terms of W71 and W81 which are available from equations 9 and 10. Thus:

(11) $W21=(Ar-\gamma Ar)/N2$

(12) $W41=(B-\zeta W81\ N7-\zeta W81N8)/N4$

(13) $W43=(Cr+\gamma Ar-\varepsilon W71\ N7-\eta W81\ N8)/N4$

(14) $W73=\zeta W81$

(15) $W75=\varepsilon W71$

(16) $W83=\zeta W81$

(17) $W86=\eta W81$

NET CHANGE IN PERIOD

Since the change of road length in a state in one period is the algebraic sum of the lengths entering and exiting the following relationships hold:

(18) $N1'=(1-T12-T13-T14)\ N1+W21N2+W41N4+W71N7+W81\ N8$

(19) $N2'=T12N1+(1-W21-T24)\ N2$

(20) $N3'=T13N1+(1-T34-T35-T36-T37-T38)\ N3+W43N3+W73N7+W83N8$

(21) $N4'=T14\ N1+T24N2+T34N3+(1-W41-W43-T47-T48)N4$

(22) $N5'=T35N3+(1-T56-T57-T58)\ N5+W75N7$

(23) $N6'=T36N3+T56N5+(1-T68)\ N6+W86N8$

(24) $N7'=T37N3+T47N4+T57N5+(1-W71-W73-W75-T78)N7$

(25) $N8'=T38N3+T48N4+T58N5+T68N6+T78N7+(1-W81-W83-W86)N8$

Expressions (9) to (17) and (18) to (25) provide 17 equations in 25 unknowns and the parameters ζ, ε, η, γ and κ. To obtain additional equations explicit consideration of intrinsic deterioration is necessary.

INTRINSIC DETERIORATION

In determining the intrinsic deterioration rates is was assumed that the roads worked on during a period were those that would otherwise have deteriorated out of their current state.

This being so, the length of road actually deteriorating from a particular state in one period is equal to the length that would have deteriorated instrinsically less the length prevented from deteriorating by road work. Thus, the intrinsic deterioration rates U from state i to j are given by an expression of the form:

$\Sigma Uij=\Sigma Tij+\Sigma Wij$

In particular, for those states on which no work is done (states 1, 3, 5 and 6):

(26) $Uij=Tij$

For state 2, with one permitted deterioration transition and one work transition:

(27) $U24=T24+W21$

For state 4, with two deterioration and two work transitions, the intrinsic deterioration rates cannot at first be determined explicitly since the general expression simply gives:

(28) $U47+U48=T47+T48+W43+W41$

Intrinsic deterioration from state 4

There are two 'streams' of road lengths intrinsically deteriorating from state 4—represented by U47 and U48. As just postulated more generally, it is on roads in these streams that work W43 and W41 is done. Now roads in the two streams differ only in their geometric condition and there is on balance no reason to suggest that road in one stream would be resealed (W43) or lightly reconstructed (W41) in preference to road in the other stream.

Accordingly, it was assumed that work was drawn from the two streams in proportion to the size of each stream. The sizes of streams are U47N4 and U48N4. When applied to expression (28) this assumption yields:

(29) $U47=T47+(W43+W41)\,(U47/U48)/(1+U47/U48)$

and

(30) $U48=T48+(W43+W41)/(1+U47/U48)$

which, by substitution, in turn give

(31) $U47/U48=T47/T48$

and an expression is now required for U47/U48.

Transition frequencies may be regarded as probabilities of transition, and two assumptions about these probabilities were made and incorporated in the following way.

Consider road in the state 3 condition Si Pii *which deteriorates into one of the Piii states,* and define the probability that this can happen as $\Sigma 3$, then:

$\Sigma 3=U35+U36+U37+U38$

(Similarly define $\Sigma 4=U47+U48$)

The conditional probability that this road will deteriorate specifically to an Siii condition is then:

$pSiii=(U37+U38)/\Sigma 3$

Similarly, using analogous notation:

$pSi=(U35+U36)/\Sigma 3$

$pGiii=(U36+U38)/\Sigma 3$, and

$pGi=(U35+U37)\Sigma 3$.

Continuing to consider road in state 3 which deteriorates to one of the Piii states, and now assuming that the deterioration of geometry is independent of the deterioration of surface, the conditional probability of deterioration to the SiGi condition, that is to Si Gi Piii, is given by:

$pSiGi=pSi+Pgi$

$=(U35+U36)\ (U35+U37)\Sigma 3^2$

But Si Gi Piii is state 5 and accordingly $pSiGi=U35/\Sigma 3$. Thus:

(32) $U35=(U35+U36)\ (U35+U37)/\Sigma 3$

Similarly:

(33) $U36=(U35+U36)\ (U36+U38)/\Sigma 3$

(34) $U37=(U37+U38)\ (U35+U37)/\Sigma$, and

(35) $U38=(U37+U38)\ (U36+U38)/\Sigma 3$

Now state 3 is Si Pii and state 4 is Siii Pii and there is no a priori reason why the proportions of road with good and bad geometry in state 3 should be different from those in state 4. It was accordingly assumed that in road lengths deteriorating from state 3 to a Piii state, and from state 4 to a Piii state, there was the same proportion of unsatisfactory geometry.

Further, it has already been shown that for the transition from state 3:

$pGiii=(U36+U38)/\Sigma 3$

The assumption means that $U48/\Sigma 4$ also equals pGiii. Thus:

(36) $pGiii=(U36+U38)/\Sigma 3=U48/\Sigma 4$ and similarly

$pGi\ =(U35+U37)/\Sigma 3=U47/\Sigma 4$.

Division among expressions (32) to (37) gives

$U35/U36=(U35+U37)/(U36+U38)+U47/U48$, and

$U37/U38=(U35+U37)/(U36+U38)=U47/U48$.

That is:

(38) $U47/U48=U35/U36=U37/U38$

For convenience this ratio was defined as θ and can be read as the ratio of good to bad geometry in roads deteriorating to a Piii state from states 3 and 4.

Expressions (29) (30) and (31) may now be rewritten as:

(39) $U47=T47+(W43+W41)\ \theta/(1\times\theta)$

(40) $U48=T48+(W43+W41)/(1\times\theta)$

(41) $U47/U48=T47/T48=\theta$

where $\theta=U35/U36$

Intrinsic deterioration from state 7

Road that deteriorates from state 7 to state 8 does so because the operational geometry becomes inadequate. For this reason it was held that, in constrast to other states, the road lengths worked on in state 7 are not necessarily those that would otherwise have deteriorated. That is, the probability that road in state 7 is worked on was taken to be independent of whether it was about to deteriorate to state 8. The total probability of transition of a road length from state 7 into state 8 (T78) is then given by its probability of intrinsic deterioration into state 8 times the probability that it was not worked on. That is:

(42) $T78=U78\times(1-W71-W73-W75-W76)$

ADDITIONAL RELATIONSHIPS

Consideration of intrinsic deterioration has thus produced the relationship:

$T47/T48=U35/U36=U37/U38=\theta$

but from (26),

$U35=T35,\ U35=T36,\ U37=T37$, and $U38=T38$

Therefore:

(42) $T47/T48=T35/T36=T37/T38+\theta$

It was next assumed that the rate of intrinsic deterioration from an Si condition to an Siii condition was independent of pavement structural condition. Applying this to the Si Pi and Si Pii states 1 and 3 yields[1]:

$U34+U37+U38=U12+U14$

and from (26) then,

$T34+T37+T38=T12+T14$

Assume also that T37+T38 is small compared with T34 and T12+T14, as T37x and T38 represent unlikely events[2]. Then:

(43) $T34=T12+T14$

If the intrinsic deterioration rate of pavement structure from Pii to Piii is assumed to be independent of seal condition, then the Pii to Piii transitions from states 3 and 4 occur intrinsically at the same rate. Thus:

$U35+U36+U37+U38=U47+U48$

and, applying (26) and (40),

(44) $T35+T36+T37+T38=T47+T48+W43+W41$

In the Si Piii states 5 and 6 the probability of seal deterioration was held to be independent of geometric condition and therefore:

(45) $T57+T58=T68$

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1. When the sealing course condition is measured in years since resurfacing, this assumption is less palatable. It implies that the seal age distributions in states 1 and 3 are such that the fraction 9 years old is the same in each state. (This would be true if, for example, most road entering state 3 did so at zero seal age—that is, through work rather than deterioration—given that pavement structure deteriorates more slowly that the seal).

2. The subsequent numerical application of this algebraic analysis gave values of T37+T38 between 1/3 and 1/40th of T34 and T12+T14 except for Tasmanian Legal class 3 roads where T38+T37=0.05 and T12+T14=0.03.

The probability of geometric deterioration was assumed to be the same for all Piii states since the bulk of road in these states would be of about the same age since reconstruction last provided an opportunity for geometric improvements. Thus, considering (26) and (42):

(46) T56+T58=T78/(1-W71-W73-W75)

Applying the assumed independence of seal deterioration from pavement structure deterioration to the probability of transition from the Si Pi condition to the Siii Pii condition gives:

U14=(U12+U14) (U13+U14), and from (26)

(47) T14=(T12+T14) (T13+T14)

Doing the same for the Si Pii to Siii Piii transitions gives:

(48) (T37+T38)=(T34+T37+T38) (T35+T36+T37+T38)

Finally, with the same assumptions of independence of seal, pavement and geometry applied to road in the Piii condition, the probability of both seal and geometry deteriorating is given by:

(49) T58=T68×T78/(1-W71-W73-W75)

Expressions (42) to (49) provide a further nine equations, but introduce the unknown θ, to give a total of 26 equations in 26 unknowns, with five indefinite parameters ζ, ε, γ, η and κ. The next step is to solve these equations to give the transition matrix elements Tij in terms of the kilometres of road work and the change of length in each state during a period, for arbitrary values of ζ, ε, γ, η and κ, the 'maintenance policy constants'.

SOLUTION

The work transition frequencies Wij are adequately defined by equations (9) to (17).

As an aid to presentation of the solution for the remaining Tij the following auxilliaries are defined:

Q1=T13/T12
Q2=T14/T12
Q3=W21N2+W41N4+W71N7+W81N8
Q4=W43N4+W73N7+W83N8
Q5=1-W71-W73-W75 Q6+1-W81-W83-W86
Q7=(N3-N3'×Q4) N4
Q8=(N4-N4'×N2-N2'-W21N2)N3
Q9=(Q8-Q7)N1-(N1-N1'×Q3) N1 N4
Q10=(Q8-Q7)N1+(N1-N1'+Q3) (N1+N3+N4)N3
Q11=(Q10-Q9) (N'-Q3)
Q12=-Q10(N1-N1'×Q3)
Q13=(N3—N3'×Q1 T12 N1—(1×Q2) T12N3+Q4)/N3
Q14=Q13+T34Q13/(Q13 -1)
Q15=N5+Q5N7-N5'-N7'+W75N7/(N5+Q5N7)
Q16=N6'+((Q15+Q18)N5+N6) (1-T68)+W86N8
Q17=N6'+Q14N3 (Q15N5+N6) (1-T68)+W86N8
Q18=(Q13 (N3+N4)-(W41+W43)N4)/(N5+Q5N7)

Find Q1, Q2, T12 34

Substitute for T13 and T14 in (18) and (47) gives:

(50) T12 (N1-N1'+Q3)/((1+Q1+Q2)N1)

(51) T12=Q2/((1+Q2) (Q1+Q2))

From (44) and (42)
$T35+T36+T37+T38=(1+\theta)T48+W41+W43$

Substituting this in (20) gives:

(52) $N3'=Q1\ T12N1+(1-(1+Q2)T12-(1+\theta)(T48-W41-W43)N3+Q4$

In (21), substitute for T24 using (19), for T34 using (43), and for T47 using (42). Eliminating $(1+\theta)(T48+W41+W43)$ from the resulting expression using (52) gives:

(53) $Q7+T12\ (Q1N1N4-(1+Q2)\ N3N4)=Q8+T12(1+Q2)\ (N1+N3)\ N3$

Since Q7 and Q8 are known from input data, (50), (51) and (53) are three equations with unknowns Q1, Q2 and T12 only.

Solving these gives:

(54) $Q1=(Q12/Q11+1)\ Q10/Q9$

(55) $Q2=-Q12/Q11$, and

(56) $T12=(N1-N1'+Q3)/((1+Q1+Q2)N1)$

The auxilliaries in these expressions are all known from the input data, for given values of γ, ε, ζ, η and κ.

Find T13, T14, T34, T24 34

(57) By auxilliary definition $T13=Q1\ T12$ and
$T14=Q2\ T12$.

From (43):

(58) $T34=T12\times Q2\ T12$

From (19):

(59) $T24=(N2-N2'+T12N1-W21N2)/N2$

Find T68, T78 and R

Transposing (52) gives:

(60) $(1+\theta)\ T48+W41+W43=Q13$

Substituting in (48) for T37 and T47 from (42), and for T35×...T38 from (44) gives:

$T38=-T34((1+\theta)T48+W41+W43)/((1+\theta)((1+\theta)T48+W41+W43\ -1))$

Substituting from (60) then gives:

(61) $T38=-T34\ Q13/((1+\theta)\ (Q13-1))$

Substituting in (44) for T47, T35 and T37 from (42) gives:

$T36=Q13/(1+\theta)-T38$

Then, using (60) and (61):

$T36=(Q13+T34\ Q13/(Q13-1))/(1+\theta)$

(62) That is: $T36=Q14/(1+\theta)$

and using (60) and (42):

$T47=(Q13-W43-W41)\ \theta/(1+\theta)$

Substituting in (22) for T35 from (42), for T57 from (45), for T56 from (46), and for T58 from (49) gives:

(64) $N5'=\theta T36N3+(1-T68-T78/Q5+T68\ T78/Q5)N5=W75N7$

Substituting in (23) for T56 from (46) and for T58 from (49) gives:

(65) $N6' = T36N3 + (N5\ T78/Q5 + N6)\ (1 - T68) + W86N8$

Substituting in (24) for T37 from (42), for T57 from (45) and for T58 from (49) gives:

(66) $N7' = \theta T38N3 + T47N4 + (T68 - T68\ T78/Q5)N5 + N5 + (Q5 - T78)N7$

After substitution in (64) and (65) for T36 from (62), and in (66) for T38 and T47 from (61) and (63), (64), (65) and (66) become three equations in the unknowns θ, T68 and T78 only. Solving these gives:

(67) $T68 = (N5 + N6 - N5' - N6' + Q14N3 + W75N7 + W86N8)/(N5 + N6)$

(68) $T78 = Q5(Q15 + \theta Q18/(\theta + 1)$,and

(69) $\theta = -Q17/Q18$

Finding remaining unknowns

The remaining unknowns can be determined simply from the preceeding solutions.

From (49):

(70) $T58 = T68 \times T78/Q5$

From (45):

(71) $T57 = T68 - T58$

From (46):

(72) $T56 = T78/Q5 - T58$

From (60):

(73) $T48 = (Q13 - W41 - W43)/(1 + \theta)$

From (61):

(74) $T38 = -T34Q13/((1 + \theta)\ (Q13 - 1))$

From (62):

(75) $T36 = Q14/(1 + \theta)$

From (42):

(76) $T47 = \theta T48$

(77) $T35 = \theta T36$,and

(78) $T37 = \theta T38$

BOUNDARY CONDITIONS

The solution for the transition matrix elements leaves in doubt the values of the maintenance policy constants γ, ε, η, ζ and κ. Given that the purpose of the analysis was to find an approximate transition matrix that could be refined by calibration, this is not unreasonable. However, it became clear during the study that guidance was required in establishing initial values for the constants.

To this end, a set of upper and lower bounds was established for each parameter. The boundary conditions were derived from the knowledge that as all the transition matrix elements are probabilities their values must be betwen zero and one. For the same reason, the sum of the elements describing transitions out of a particular state must be less than or equal to one.

Not all of the possible relationships were explored, but the following useful boundary conditions were derived.

Kappa

κ<=(N7+N8–E)/(N8–E)

κ>=N7(D+E–N7–N8)/(D(N8–E))+1

κ<=(N7+N8–E)/D

κ>=0

Zeta

ζ<=(N1–N1′+A+B+D+E)/(W81(N7+N8))

ζ>=(-N1'=A×B=D×E)/(W81(N7=N8))

ζ<=1–1/W81

ζ>=(1–W71)/W81

ζ<=0

Note also that when the annual length of light reconstruction is negligible ζ=0 approximately.

Epsilon

ε=<(1–ζW81)/W71–1

ε=<0

Eta

η=<1/W81–ζ–1

η=>0

CALCULATION SEQUENCE

The sequence of operations used to obtain the approximate transition matrix was as follows;

Input state vectors at start and end of period
Input lengths of roadworks in period
Evaluate boundary conditions for κ
Select and input κ
Calculate W71 and W81 from (9) and (10)
Evaluate boundary conditions for ζ, ε and η
Select and input ζ, ε, η and γ
Calculate work rates Wij from (11) to (17)
Evaluate auxilliaries Q7 to Q12
Evaluate auxilliaries Q1 and Q2 from (54) and (55)
Calculate T12, T13, T14, T34, and T24 from (56), (57), (58) and (59)
Evaluate auxilliaries Q13 and Q14
Calculate T68 from (67)
Evaluate auxilliaries Q15 to Q18
Calculate θ from (69)
Calculate T78, T48 and T38 from (68), (73) and (74)

Calculate T36, T35, T37 and T47 from (76), (77), (78) and (76)

Calculate T58, T57 and T56 from (70), (71) and (72)

Calculate elements on leading diagonal (T11, T22 etc) as 1- sum of other transitions out of the state. For example, T11=1-(T12+T13+. . .+T18)

If matrix has elements with negative values revise maintenance policy constants and recalculate matrix.

Calculate intrinsic deterioration rates from (26), (27), (39), (40) and (42).

APPENDIX II—ASSUMPTIONS AND LIMITATIONS OF THE METHOD

In discussing the assumptions and limitations of the method explored in this study it is useful to refer to the methodology of gas thermodynamics. Thermodynamics deals with systems purported to be in equilibrium or to behave quasistatically, and clearly separates phenomenological descriptions from statistical decriptions. Such idealizations are also fundamental to this study. Further, thermodynamics draws a distinction between the theoretical skeleton of a model and the experimental determination of numerical values which give the model practical shape, a distinction which is also necessary in a commentary on this study.

To the thermodynamicist, an equilibrium system is one for which a single gross observation does not produce evidence of changes taking place over time. A State's road system is of this nature as discussed in Chapter 2 and illustrated by Figure 2.3. Taken literally, the thermodynamicist's definition is empty in that there are no such systems. Nevertheless, that science has argued successfully that there is no option but to assume that a system which appears to be in equilibrium is in equilibrium. Parameter values are taken to be independent of the rate of change of the parameter with time. This is analogous, for example, to initially ignoring strain rate in structural stress calculations as is common practice. That argument has been adopted in this study to justify the assumption of constant deterioration rates and thence piecewise linear relationships. The road system's condition is held to be changing quite slowly and the rate of change is regarded as near constant. It is proposed that within the limits of experimental error any lack of equilibrium there may be has no observable consequences.

Phenomenological thermodynamics deals exclusively with systems in bulk, that is, with their properties as directly revealed by gross observation. It does not recognise fine structure and pretends that it is irrelevant whether a system is ultimately continuous or particulate matter. The input of detailed information about the system is small and the output correspondingly lacks detail. It leads to general relationships between descriptors but is unable to say why the descriptors take particular values. This is the approach adopted for the present study. Statistical thermodynamics regards a system as a large number of particles and is based on the premise that the gross behaviour of the system is an aggregate manifestation of the motion of individual particles. Because it is quite impracticable to specify all particle motion in detail, the thermodynamicist is content to use representative values of variables (ie statistics) which pertain with certain probabilities.

These two approaches give rise to two distinct sets of physical descriptors the statistical and the phenomenological, and these ought to correspond to the extent that the phenomenological is derivable from the statistical. Analogously, the model developed in the present study is a discrete or piecewise representation of a behavioural continuum more precisely described by some complex and unknown continuous probability distribution. One reason the Markov chain technique was used was that it can be viewed as providing just such a representation.

The statistical information needed to prepare a more precise description of road pavement behaviour is not yet available. Thus the statistical thermodynamics approach cannot be adopted. Further, the present model absorbed all useful available data. This almost completely precludes rational quantitative evaluation of the errors in both the theoretical skeleton and the numerical values for the model described in this paper.

What follows is therefore confined to qualitative discussion.

Much of the value of the model outlined in this paper lies in its relative simplicity, yet, that simplicity depends upon various features of the model which limit its validity and applicability. These limitations are to be found in:

- the extent to which the Markov chain process represents actual road system behaviour;
- the validity of the assumptions employed in the practical implementation of the Markov method; and
- the reliability of the estimation of the model's parameters.

BEHAVIOUR REPRESENTATION

The projections of condition and road work resulting from this study rest on the following propositions:

- lengths of road may be categorised according to their pavement condition and will move between any two categories in a non-random way; and
- the proportions of the road lengths in a particular category that move to other categories in each year as a result of both maintenance and deterioration
  - —are independent of which particular road lengths are in the category and therefore, for example, are independent of the construction quality and maintenance history of the road lengths in the category
  - —and do not vary with time for any other reason.

That is, the behaviour of a road network has been modelled as a discrete-state, homogeneous Markov chain process. The life cycle of any road section has been partitioned into a set of discrete states characterised by a three-parameter description of its pavement condition.

Variation with time

Consider the constancy of the transition frequencies. If funding has been such as to have sustained repair maintenance activities over a number of years, reliability theory suggests that the road system would eventually behave homogenously, assuming that the stresses on the system remain the same, which they do not. The increasing stresses and intrinsic deterioration rates resulting from traffic increases have not been modelled. While it might be accepted that roads are constructed to meet the predicted traffic (so that the average design life or deterioration rate across the system is constant over time even though traffic increases) it is not clear that new construction has been sufficiently continuous in the recent past to permit this assumption. The proposition that the maintenance policy of a road authority can be accurately represented, as one in which a constant proportion of the road requiring certain types of maintenance actually received that maintenance, is also somewhat dubious. While the proposition that this will be so in the future is a reasonable premise on which to base projections, it is quite evidently not an accurate description of the past as revealed by available data. Still, it is one method of describing the imperfect repair maintenance that characterises road system management and was used principally to find past *average* values of intrinsic deterioration rates.

Similarity of roads

The proposition that the relative frequency of transitions is independent of which road lengths actually compose a condition state means, firstly, that the distribution of durability among road lengths with a given pavement condition should remain constant over time.

This might be so if the current durability of a length of road were independent of the sequence of pavement conditions and maintenance actions it experienced in reaching the current pavement condition.

It is more likely to be so if road lengths deteriorate independently of one another than if they do not. It might also be so if these factors always combine in some other unspecifiable way to give a constant distribution of durability.

This proposition means secondly that:

- either the likelihood of a particular length of road being worked on is dependent only on its condition and not on its perceived importance or on its geographic location, etc; or
- that the distribution of importance and location etc remains constant over time for all roads within a single pavement condition state.

By way of illustration, this proposition taken overall suggests that there should be no difference in the net deterioration rate of a reconstructed road in its third reseal state and a rehabilitated road in its second reseal state irrespective of their geographic locations. Given appropriate road design philosophy, this situation is plausible but not necessarily likely. It may be thought necessary to establish whether design practice is intended to produce some sort of equivalence in performance and design life, or whether, because of some other design objective such as the optimisation of life cycle costs, planned stage construction etc, road deterioration rates will differ or maintenance decision criteria will vary according to the state-history of the road.

In an attempt to ensure that this proposition remained valid, the numerical work in this study treated together only those roads that:

- were likely to have been constructed to the same standards vis-a-vis prevailing traffic;
- carried roughly the same traffic;
- were likely to be perceived as equally important;
- were in similar geographic locations; and
- were treated as one class for the purposes of maintenance funding.

The road sets studied were dominated by rural or outer urban sealed arterials and were subdivided during analysis according to State, and according to State legal classifications such as State Highways, Main Roads, and Secondary Roads. Roads that were known to have been the subject of major changes in maintenance policy between 1971 and 1981 (eg roads that became national highways) were excluded from the study where possible.

The proposition that the relative frequency of transition is independent of which road lengths actually compose a condition state, contains the proposition that the future behaviour of road in a given state is independent of its maintenance history. From a phenomenological viewpoint this may generally be so. However, there is one place where this proposition is likely to falter. This is in the possible dependence of the probability of reconstruction on the number of times a road length has been re-sheeted or resealed. The numerical consequences of any dependence in the past have simply been modelled, rather than attributed to a causual effect which may alter as part of maintenance policy.

Random behaviour

Finally there is the proposition that roads change pavement condition in a statistically predictable way. This is the proposition that, if the condition of road pavements were to be examined at intervals and the changes recorded, the record would show a consistency which permitted a probability to be confidently assigned to the occurrence of any particular type of change during an interval; and that many different values for that probability would not be seen to occur with nearly equal frequencies, for example.

This study has some of the appearances of working from an established tabulation of such probabilities. It did not in fact do so. The key element of the study was the derivation of these probabilities, not by direct observation of changes, but by observation of the accumulated effect of the changes and the assumption that changes accumulate in the specific ways the previous propositions will admit. The assumption of statistical predictability in the rural road system has not been verified and this would be a difficult task.

Each of the propositions discussed above is in fact a specification of predictability. The fewer of these propositions accepted, the less predictable road pavement behaviour is held to be. Alternative but functionally equivalent propositions could have been made, but it does seem that those adopted represent the minimum set necessary for a projection by any reputable means from the available data.

There is a body of road condition data held by the Victorian Road Construction Authority which, while not useful in the present study, might submit to transition protocol and frequency analysis in a future investigation of the validity of these propositions.

VALIDITY OF IMPLEMENTATION

Three important, persistent assumptions were made in implementing the general theory. The first was that the intrinsic rates of deterioration observed over the past ten years will continue to apply in the next ten years. Over and above the preceding discussion of constancy, the model also assumed a constant ratio between the lengths of roads with acceptable and unacceptable geometry in the roads deteriorating beyond state 4. While this may be valid for short periods, it is clearly not so for longer periods when maintenance policies are deliberately chosen so as to correct geometric deficiencies.

The numerical effects of this simplification are not fully known. It does influence the calculated distribution of bituminous resheeting between states 7 and 8 and state 4, and thus the lengths of road in states 3, 5 and 6.

The third and more obvious assumption was that of past maintenance efficiency. It was assumed throughout the study that, in the past:

- work was done only on those road lengths that required it;
- no work was done on road lengths with sound wearing and sealing courses; and
- the road lengths worked on were among those that would otherwise have deteriorated in the coming year.

While this may be good work scheduling practice, there is simply no guarantee that it happened, and some suggestion that it did not.

The accuracy with which this assumption was implemented depends crucially on the method of selection, or choice of description, of the condition states. Because available pavement condition data were set not in terms of work required but in terms of roughness and age, it was necessary to adopt a form of correspondence between roughness and age and work required. The correspondence chosen was based on the best information available but its reliability is unknown. These sorts of assumed correspondence are present in nearly all roadworks planning techniques. One of the features of the method described in this study is that it brings such assumptions into the open, where they can be seen and manipulated.

PARAMETER ESTIMATION

The accuracy of the projections made in this study is almost directly proportional to the accuracy of the 1972 and 1981 state vectors and the work rates for the period.

Errors in condition vector evaluation

The level of confidence in the condition vectors, as accurate pictures of the actual distribution of condition in the road system, is chiefly a matter of the expectation of errors in the inventory data on which the vectors are based. Confidence in the predictive capability of the model is governed mainly by the likelihood of errors in the mapping functions which attempt to match the two sets of condition data.

Inventory errors

The errors which may exist in the inventory records and that occurred during the data collection phase of the surveys may be considered to be of two types. Objective errors are instrument errors in measurements of data such as roughness, grades, widths, speeds and AADT. There is little that can be done to quantify them, but generally these sorts of errors will be randomly distributed about the true values and will not be large. As such they will not be significant at the aggregate level. The specific data items in which this sort of error may occur are as follows:

- ARS Average Highway speed weighting calculations and design speeds may be in error but not significantly so.
- ARS Seal width is reported as the average value for the section. Again, the probable errors are not significant.
- ARS traffic volume information is very patchy in most rural areas and often had to be estimated either from traffic counts up to 10 years old adjusted using traffic growth indices, or estimated from other data on adjacent roads and knowledge of local land use and development, using procedures described in Appendix C of the ARS Specifications Manual. Errors in the AADT may be quite large.
- Errors may have occured in roughness measurement for the NDB through the incorrect operation of the NAASRA Roughness Meter, either by the crew or by instrument malfunctions; such errors would be random. Systematic biassing errors would come about if the meters were not properly calibrated and correlated; these errors are more serious.
- Measuring the lengths of curves and their speed ranges is not precise. Accordingly, the NDB vertical and horizontal curve speeds may be inaccurate.

Subjective errors are those which occur in data items with values estimated by the surveyors rather than measured. Errors of this type are likely to show some bias consistently in one direction, either too high or too low, or to have a central tendency error. This error does not necessarily disappear in large populations as random-type errors might do. A problem with subjectively-based data is being able to make value comparisons between two sets of data collected at different times or places, because perceptions and expectations can vary greatly. Subjective errors arise in the following data.

In the ARS, structural condition is a visual estimate made by the roads engineers of the remaining life. The condition of the sealing course can be misleading in this process. Note that the life expectancy of most pavements is greater than the time for which most of the assessors are able to work on the road system and become familiar with road behaviour. Varying design methods and materials have been used as new techniques have been introduced, and the way more recently built roads will behave in comparison with earlier roads is often unknown and open to conjecture. Assessors can be influenced by the opinions of their peers and by the collective attitude of the State road authority. The size of the error could be estimated only if adequate work records existed and if the pavement life were known. Surface condition in the ARS and surface rating in the NDB, is a subjective estimate made by the road engineers of the remaining seal life. This estimate is thought to be less susceptible to error because the signs of deterioration are more visible than those of a pavement's structure which are at first largely hidden.

The assessment of the Present Servicability Rating on a 5-point scale in the NDB is also subjective and therefore prone to several types of error. The likely errors are of the same order as those which might be expected in ARS structural condition estimates.

Mapping Function Errors
The mapping functions used in this study to express the inventory data in the two surveys in equivalent terms may themselves introduce errors, and these can be highly significant.

The ERVL curve used to convert structural condition (in years) to roughness (in counts/km) describes only an empirical relationship whose variability is large but unknown and whose coefficient of correlation is generally low. The type of scattergram to be expected can be deduced from Figure 2.3. The precision of the mapping is not considered to be high, especially for roads past their mid-life point. However, the pavement condition descriptor P may take only three values, each covering a broad range of roughness levels, so the description of pavement condition should not be particularly sensitive to the goodness-of-fit of the ERVL curves.

Before the ERVL function could be used, ARS Structural Condition data was converted to Pavement Age. This required a credible determination of the original surveyor's personal value of mean pavement life for each class of road. The various ways of calculating this pavement life give a wide range of possible values (approximately 20–60 years). Variations in estimates of pavement life can induce large changes in the pavement condition distribution and it is concluded that the pavement life function is a likely source of serious error in the illustrative projections. It should be noted that, though the analysis of the State road system was done on a State legal class basis in this study (because that is the basis for the road policy formulation, design and accounting), the ERVL relationships and pavement life functions are on a road functional class basis.

Seal age was used as a proxy for seal condition in the numerical work of this study. A resealing interval was used to convert Surface Condition in ARS data and Surface Rating in NDB data to seal age to make them compatible with Year of Reseal data in NDB. Errors in the selected interval would produce a systematic bias, which may invalidate comparisons between 1972 and 1981 and lead to false conclusions being drawn. The extent of this depends on how much of the 1981 seal condition distribution was determined from Year of Reseal and how much from Surface Rating. If only Surface Rating data are used, this problem of bias disappears since 1972 and 1981 results would then depend equally on the frequency of reseal. The resealing interval is typically in the range 8 to 12 years, and estimation of the correct value is most likely to be the source of greatest error in seal condition evaluation.

Errors in work rate estimates

Quite serious difficulties emerged in endeavouring to obtain accurate measures of actual work output from annual reports, due to shortcomings in the extent and precision of the reporting. These included:

- incomplete time series of data because of changes in data collection policy;
- format changes in the reporting of data from year to year such as changes in categorisation and definitional changes;
- inadequate or inappropriate cross-tabulation of summary data;
- projects stretching over several years may have the same work reported in several successive reports and a careless summation of the reported work may lead to over-estimation of the work output;
- failure to report works through an oversight, by excluding mention of those projects below a certain size and importance (which may lead to large cumulative errors), or by leaving out those works conducted on rural arterials by local government on behalf of the State road authority);

- only partial descriptions of projects, for example the project type may be stated but the length of work not reported; and
- ambiguous descriptions of road works.

Ambiguous descriptions of road works were the most problematic aspect of utilising the annual reports for calculating work rates. Although the principle of standardisation of the usage of road engineering terminology has been put forward and promoted by the Standards Association of Australia and NAASRA, it does not appear to have been widely adopted by the State road authorities The use of putatively standard nomenclature in the recording of the pavement work and surfacing work types is idiosyncratic. The terms themselves are often more generic than specific and definitions or explanations are not proffered. Particularly vexing is the use of general terms to cover a gamut of work types which are quite different in unit costs and road condition change. Two prime examples of this practice are the terms 'resealing', which may be taken to mean anything from primer sealing through spray sealing, hot-mix resealing etc to bituminous concreting; and 'reconstruction', which may encompass light reconstruction, overlays, rehabilitation, deep reconstruction of the pavement structure, widening, and even complete realignment. In short, descriptions of road work are often vauge or ambiguous and open to misinterpretation. Consequently some judgement had to be exercised in the use of the reported works information to determine what had been done.

Where possible, supplementary data were sought from the road authorities in the States analysed but residual uncertainties about work rates remain.

APPENDIX III—ROAD SYSTEMS DATA

DESCRIPTION OF ROAD SYSTEMS

Notes on Tasmanian road system and road system changes

Tables III.1, III.2, and III.3 provide summary descriptions of the three sets of roads in Tasmania which were modelled in this study. They show, for roads which were rural or outer urban arterials in 1981:

- road names and equivalent road numbers in 1972 and 1981;
- total (sealed plus unsealed) road length surveyed in 1972 (ARS) and 1981 (NDB) for each road;
- sealed road length surveyed in 1972 (ARS) and 1981 (NDB) for each road;
- nett changes in seal lengths; and
- causes of changes in sealed lengths of roads declared to be in the particular legal class.

Notes on Victorian State Highway System

State Highways in Victoria (coded as State Legal Class 2 roads) are the principal arterials forming interstate connections and links between the larger centres of population in the State. Roads which are National Highways were included in the analysis of the Victorian State Highway system, primarily because the roadwork done on them could not be separately identified.

Table III.4 lists the names and identification numbers of the road making up the Victorian State Highway system analysed in this study. The data for 1972 was estimated from the ARS survey rural roads inventory file, and the description of the road system in 1981 was taken from the NDB sectionised inventory file for rural roads.

While Table III.4 attempts to attribute the observed change in measured seal length of each individual highway to some specific action, a measure of judgement was needed to arrive at the figures given because the information contained in the annual reports was insufficient. The totals given for construction will not exactly tally with those given in tables relating to roadwork.

CONDITION VECTOR ADJUSTMENT

Normalisation of vectors

In order to use the raw state vectors drawn directly from the ARS and NDB to determine the average transition rates effective between 1972 and 1981 it was necessary that the vector changes due solely to deterioration and maintenance be identified. The first step in this process was to estimate the change in each state that was attributable to the changes in length described in Tables III.1 to III.4. Changes due to new declarations and unknown causes could not be said to have happened to roads in any particular state and were treated in the following way:

- Calculate S = 1981 raw condition vector − 1972 raw condition vector

  S = Vector of actual change in road length in each state between 1972 and 1981

- Calculate Total Error = Total road length in 1981–Total road length in 1972–C

  Where C = Total new sealed road construction over the 1972–81 period
- Calculate state Error E = $\frac{\text{Total error x road length in state in 1972}}{\text{Total road length in 1972}}$

  E = Vector of the total error distributed across all eight condition States in proportion to the length of road in those States
- Calculate S* = S–E

  S* nett = Normalised vector of corrected length changes in each State between 1972 and 1981

Length changes due to new construction and initial sealing were known to he additions to state 1 and were subtracted from state 1 of the S* vector, which then became the vector of changes due solely to deterioration and maintenance, The S* vector was then added to the 1972 vector to give a 1981* vector describing the condition that would have prevailed in 1981 had there been only deterioration and maintenance in the preceding 10 years.

Calibration vectors

The program which calculated approximate transition matrices required two vectors one year apart that could be taken as representative of the road system between 1972 and 1981. These were produced in the following way:

- Calculate a first vector I = (1972+981*)/2
- Calculate dS = S*/9

  dS = Vector of corrected average annual rates of change of length of each State over the nine-year period
- Calculate a second vector

  F = I+ dS

The road sets analysed calculations are tabulated in Tables III.5 through III.8 for each of the road sets analysed.

TABLE III.1—TASMANIA; LEGAL CLASS 1 ROADS, STATE HIGHWAYS

(carriageway.km)

	Road no		Total road length		Sealed road length		Source of variation in sealed length of declared road			
							Construction			
Road name	*1972*	*1981*	*1972*	*1981*	*1972*	*1981*	*new road*	*new seal*	*Declaration*	*Unknown*
East Derwent	na	A0029	0.00	14.24	0.00	14.24	14.24			
Lake	1010	A0100	149.83	149.48	59.87	82.63		22.76		
Tasman	1011	A0113	411.31	410.64	411.00	409.17				-1.83
Arthur	1014	A1042	72.74	72.69	72.74	72.69				-0.05
Channel	1015	A0155	47.56	45.02	47.56	45.02			-2.54	
Huon	1016	A0168	95.78	92.88	95.78	91.35				-4.43
Southern Outlet	1017	A0171	10.15	14.85	10.15	14.85	4.70			
Lyell	1019	A0197	283.23	278.87	265.00	278.41		13.41		
Bass	1024	A0249	133.80	133.80	133.80	133.80				
West Tamar	1025	A0252	39.97	40.00	39.97	40.00				+0.03
East Tamar	1026	A0265	41.29	37.90	41.29	37.11				-4.18
Stanley	1035	A0559	8.09	8.06	8.09	8.06				-0.03
Waratah	1039	A0391	71.75	71.05	71.75	69.11				-2.63
Marlborough	1044	A0443	31.52	31.93	0.21	0.20				-0.01
Zeehan	1047	A0472	35.82	35.49	35.82	35.49				-0.33
Murchison	1048	A0485	78.54	77.89	78.54	77.89				+0.35
Total			1510.28	1514.8	1371.3	1410.1	18.44	36.17	-2.54	-13.11

na not applicable

TABLE III.2—TASMANIA; LEGAL CLASS 2, MAIN ROADS

(carriageway.km)

	Road no		Total road length		Sealed road length		Source of variation in sealed length of declared road			
							Construction			
Road name	*1972*	*1981*	*1972*	*1981*	*1972*	*1981*	*new road*	*new seal*	*Declaration*	*Unknown*
Ridgley	1101	A1015	16.36	15.94	16.36	15.94				-0.42
Wilmot	1102	A1028	30.17	29.83	30.17	29.83				-0.34
Sheffield	1103	A1031	34.33	34.60	34.34	34.60				+0.26
Frankford	1104	A1044	60.27	60.82	60.27	60.82				+0.55
Low Head	1105	A1057	22.22	22.00	22.22	22.00				-0.22
Lilydale	1107	A1073	18.45	19.41	18.45	19.41				+0.94
Ringarooma	1108	A1086	7.47	7.50	7.47	7.50				+0.03
Evandale	1110	A1109	7.00	6.19	7.00	6.19				-0.81
Esk	1112	A1125	72.60	72.82	72.60	72.82				+0.22
Fenton	1114	A1141	21.93	23.41	23.20	23.41				+0.21
Colebrook	1115	A1154	40.24	43.07	40.24	43.07			+2.83	
King Island	1121	A1219	69.26	31.50	35.48	31.50				-3.98
Bruny	1122	A1222	46.50	38.84	3.14	8.08		4.94		
Nicholl's Rivulet	1124	A1248	17.94	17.86	17.94	17.86				-0.08
Railton	1125	A1251	33.45	33.63	33.95	33.63				-0.32
Port Sorell	1132	A1329	14.93	10.88	11.26	10.88				-0.62
Castra	1133	A1332	32.50	31.90	32.50	31.44				-0.06
Preston	1134	A1345	21.77	21.87	21.77	21.87				+0.10
Stoney Rise	1135	A1358	4.44	4.03	4.44	4.03				-0.41
Mole Creek	1137	A1374	23.46	23.17	23.45	23.17				-0.28
Blackmans Bay	1139	A1390	3.52	3.50	3.52	3.50				-0.02
Bridport	1140) 1287)	A1400	55.10	69.00	55.10	69.00	7.50	6.40		

TABLE III.2(Cont)—TASMANIA; LEGAL CLASS 2, MAIN ROADS

(carriageway.km)

	Road no		Total road length		Sealed road length		Source of variation in sealed length of declared road			
							Construction			
Road name	*1972*	*1981*	*1972*	*1981*	*1972*	*1981*	*new road*	*new seal*	*Declaration*	*Unknown*
Irishtown	1141	A1413	7.09	7.05	7.06	7.05				-0.01
Lake Leake	1144	A1442	62.16	59.19	1.45	10.44		9.01		
Illawarra	1146	A1488	14.93	15.11	15.93	15.11				+0.18
Pine	1149	A1497	18.56	18.03	18.57	18.03				-0.54
Gladstone	1150	A1507	24.89	24.95	24.89	24.95				+0.06
Mersey	1153	A1536	9.75	9.94	9.75	8.63				-0.92
Devonport	1154	A1549	2.81	3.99	2.81	3.99			+1.18	
Forth	1155	A1552	10.64	10.54	10.64	10.54				-0.10
Lady Barron	2216	A1565	28.16	28.42	17.30	28.42		10.12		
Bell Bay	na	A1581	na	2.23	na	2.23			+2.23	
Total			800.40	805.7	682.3	720.4	7.50	30.47	+6.24	-5.43

na not applicable

TABLE III.3—TASMANIA; LEGAL CLASS 3, 5 & 6 SECONDARY, SUBSIDISED AND DEVELOPMENTAL ROADS

(carriageway.km)

	Road no		*Total road length*		*Sealed road length*		*Source of variation in sealed length of declared road*			
							Construction			
Road name	*1972*	*1981*	*1972*	*1981*	*1972*	*1981*	*new road*	*new seal*	*Declaration*	*Unknown*
Storys Creek	1202	A2027	20.9	15.48	0.19	10.41		10.22		
Rossarden	1203	A2030	5.0	18.03	2.16	18.03	13.0	2.87		
Nubeena	1204	A2043	29.12	27.86	3.97	27.86		23.89		
South Arm	1206	A2069	28.86	28.16	28.85	28.16				-0.70
Leighlands	1208	A2085	4.29	4.26	4.29	4.26				-0.03
Sandfly	1209	A2098	9.49	9.34	1.53	9.34		7.81		
Grass Tree Hill	1218	A2182	11.23	13.01	0	9.75		9.75		
Boyer	1221	A2218	17.39	17.72	5.36	17.72		12.36		
Mathina	1224	A2247	26.66	26.83	2.75	4.17		1.42		
Pipers River	1226	A2263	31.23	31.47	31.32	31.41				+0.18
Corinna	1282	A2823	63.22	37.97	38.28	37.97				-0.31
Pardoe	1284	A2849	1.51	1.52	1.51	1.52				+0.01
Batman	1286	A2865	12.71	12.62	11.26	12.62		1.36		
Poatina	1288	A2881	45.87	46.16	45.87	46.16				+0.29
Maydena	1310	A3107	13.18	12.64	13.18	12.64				-0.54
Barnes Bay	1311	A3110	2.00	0.93	0.89	0.91				+0.02
Kettering	1312	A3123	0.72	0.70	0.72	0.70				-0.02
Total			291.60	305.70	192.05	273.63	13.0	69.68		-1.10

TABLE III.4—VICTORIA; LEGAL CLASS 2, STATE HIGHWAYS, RURAL DIVISIONS

(carriageway.km)

	Road no		Sealed road length		Source of variation in sealed length of declared road			
					Construction			
Road name	*1972*	*1981*	*1972*	*1981*	*new road*	*new seal*	*Declaration*	*Unknown*
Wimmera	2110	2111-2	224.58	223.30			-1.28	
Princes West	2500	2500-5	433.24	385.60	44.77		-92.41	
Princes East	2510	2511-6	430.44	431.69	32.47		-31.22	
Western[a]	2520	2521-5	387.67	352.35	9.30		-44.62	
Calder	2530	2531-6	527.03	521.98			-5.05	
Northern	2540	2541	144.26	163.71			+19.45	
Hume[a]	2550	2551-3	246.66	194.63	15.80		-67.83	
Omeo[b]	2560-1	2561-4	183.81	202.43		20.62		
Murray Valley[c]	2570	2571-4	722.25	730.27		7.98		
South Gippsland	2580	2581-3	199.10	197.91				-1.19
Midland[d]	2590-3	2591-8[g]	450.09	446.03	14.62		-18.68	
Bonang[e]	2600	2601	34.67	40.34		5.67		
Sturt	2610	2611	117.41	117.41				-0.35
Henty	2620	2621-3	394.91	336.96	4.40		-62.35	
Loddon Valley	2630	2631	114.92	114.83				-0.09
Goulburn Valley	2640	2641-2	226.97	227.40				+0.43
Ouyen	2650	2651	130.92	130.73				-0.19
Glenelg	2670	2671	283.91	283.32				-0.59
Ovens	2680	2681	76.25	76.19				-0.06
Borung	2690	2691	123.65	123.35				-0.30

TABLE III.4(Cont)—VICTORIA; LEGAL CLASS 2, STATE HIGHWAYS, RURAL DIVISIONS

(carriageway.km)

	Road no		Sealed road length		Source of variation in sealed length of declared road			
					Construction			
Road name	1972	1981	1972	1981	new road	new seal	Declaration	Unknown
Sunraysia	2700	2701	280.30	336.54			+56.24	
Bass	2710	2711	3.17	2.92				-0.25
Maroondah	2720	2721	104.65	104.61				-0.04
Bellarine	2730	2731	27.29	34.64	10.67		-3.32	
Pyrenees	2740-1	2740-1	149.52	149.73				+0.21
Cann Valley[f]	2760	2761	24.73	24.73				
McIvor	2770	2771	40.64	40.54				-0.10
Hamilton	2780	2781-3	226.88	226.29	6.43		-7.03	-0.60
Kiewa	2790	2791	78.74	78.66				-0.08
Total			6388.66	6301.38	138.46	34.27	-258.09	-3.19

a. National Highway.
b. Unsealed lengths 98.79km (1972) and 77.01km (1981).
c. Unsealed lengths 18.07km (1972) a4km (198km (1981).
d. Unsealed lengths 35.69km (1972) and 29.84km (1981).
e. Unsealed lengths 78.81km (1972) and 74.71km (1981).
f. Unsealed lengths 20.61km (1972) and 72.01km (1981).
g. Road section numbers 2591-5 inclusive plus section 2598, of which 28km is non-arterial.

TABLE III.5—TASMANIA; CONDITION VECTORS FOR LEGAL CLASS 1

(km)

	Condition state number								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Total*
1972 vector	446.8	375.6	146.7	250.5	0	4.3	2.1	145.3	1371.3
1981 vector	323.2	200.4	381.0	216.8	13.5	176.6	2.6	95.9	1410.1
S vector	-123.5	-175.2	+234.3	-33.7	+13.5	+172.3	+0.5	-49.4	+38.8
Construction C	+55.1	na	na	na	na	na	na	na	+55.1
Error E	-3.7	-2.3	-4.4	-2.5	-0.2	-2.0	0	-1.1	-16.3
S*	-174.9	-172.9	+238.7	-31.2	+13.7	+174.3	+0.5	-48.3	-0.1
1981*	271.9	202.7	385.4	219.3	13.7	178.6	2.6	97.0	1371.2
dS	-19.43	-19.21	+26.52	-3.47	+1.52	+19.37	+0.06	-5.37	-0.01
Initial vector I	359.35	289.15	266.05	234.90	6.90	91.45	2.35	121.15	1371.3
Final vector F	339.95	269.95	292.55	231.40	8.50	110.75	2.41	115.75	1371.3

na not applicable

Note: See text for explanatory notes.

TABLE III.6—TASMANIA; CONDITION VECTORS FOR LEGAL CLASS 2

(length in km)

	Condition state number								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Total*
1972 vector	164.9	428.1	10.9	51.9	0	0.9	0.2	25.4	682.3
1981 vector	367.6	215.9	70.3	44.5	0	21.1	0	1.0	720.4
S vector	+202.7	-212.2	+59.4	-7.4	0	+20.2	-0.2	-24.4	+38.1
Construction C	+37.9	na	na	na	na	na	na	na	+37.9
Error E	+0.1	+0.1	0	0	0	0	0	0	+0.21
S*	+164.7	-212.3	+59.4	-7.4	0	+20.2	-0.2	-24.4	0
1981*	329.6	215.8	70.3	44.5	0	21.1	0	1.0	682.3
dS	+18.30	-23.59	+6.60	-0.82	0	+2.24	-0.02	-2.71	0.0
Initial vector I	247.4	321.95	40.60	48.20	0	11.0	0.1	13.2	682.3
Final vector F	265.75	298.36	47.25	47.38	0	13.24	0.08	10.49	682.3

na applicable

Note: See text for explanatory notes.

TABLE III.7—TASMANIA; CONDITION VECTORS FOR LEGAL CLASS 3, 5 & 6

(km)

	Condition state number								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Total*
1972 vector	30.5	118.9	19.2	14.5	0	2.1	0	6.9	192.1
1981 vector	145.2	41.0	42.9	12.4	1.1	24.3	0	6.9	273.7
S vector	114.7	-77.9	+23.7	-2.1	+1.1	22.2	0	0	+81.6
Construction C	81.4	na	na	na	na	na	na	na	+81.4
Error E	0	+0.2	0	0	0	0	0	0	+0.2
S*	+33.3	-78.1	+23.7	-2.1	+1.1	+22.2	0	0	+0.1
1981*	63.8	40.8	42.9	12.4	1.1	24.3	0	6.9	192.2
dS	+3.70	-8.68	+2.63	-0.23	+0.12	+2.47	0	0	+0.01
Initial vector I	47.15	79.85	31.05	13.45	0.55	13.2	0	6.9	192.1
Final vector F	50.85	71.17	33.68	13.22	0.67	15.65	0	6.9	192.1

na not applicable

Note: See text for explanatory notes.

TABLE III.8—VICTORIA; CONDITION VECTORS FOR LEGAL CLASS 2, RURAL DIVISIONS

(km)

	Condition state number								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*Total*
1972 vector	3278.22	1152.85	443.55	950.55	12.86	80.53	118.15	351.98	6388.66
1981 vector	3421.39	1123.49	975.78	239.61	187.56	98.51	56.24	98.80	6301.38
S vector	+143.17	−29.36	532.23	−710.94	+174.70	+117.98	−61.91	−253.18	−87.27
Construction C	+177.62	na	na	na	na	na	na	na	+177.62
Error E	−135.93	−47.86	−18.39	−39.41	−0.53	−3.34	−4.90	−14.59	−264.89
S*	+101.48	+18.44	550.63	−671.53	+175.23	+121.32	−57.01	−238.59	−0.03
1981*	3379.69	1171.29	994.17	279.02	188.09	201.85	61.14	113.39	6388.66
dS	+11.27	+2.05	+61.18	−74.61	+19.47	+13.48	−6.33	−26.51	0.0
Initial vector I	3328.96	1162.07	718.86	614.79	100.49	141.19	89.64	232.69	6388.66
Final vector F	3340.23	1164.12	780.04	540.17	119.95	154.67	83.31	206.18	6388.66

na not applicable

Note: See text for explanatory notes.

APPENDIX IV—CALIBRATION RESULTS AND SENSITIVITY TESTS

SENSITIVITY TESTS

Many sensitivity tests were carried out during the course of the study. These tests explored the consequences of errors in parameters to which values were, perforce, somewhat arbitrarily assigned. The tests which revealed the largest likely errors in pavement condition projections were those examining the effect of 'pavement life' in 1972 and resealing interval on the condition state vector.

In order to investigate the influence of assumptions about the pavement life adopted during the 1972 ARS, several 1972 state vectors were calculated from Tasmanian ARS data using the different values of pavement life shown in Table IV.1.

During this analysis the roughness threshold, seal ages and geometric definitions of each condition state were held constant. The roughness thresholds used for this purpose are shown in Table IV.2. The resulting state vectors are shown in Table IV.3.

Table IV.3 illustrates the particular sensitivity of 1972 state vectors to assumed values of pavement life. The state vectors obtained for 1981 did not vary with pavement life as there were sufficient data to infer 1981 structural condition by more direct means.

The threshold point at which a seal was assumed to change from satisfactory [S] to unsatisfactory [$\bar{S}$) was tested at two values to assess what changes were wrought

TABLE IV.1—PAVEMENT LIVES USED IN SENSITIVITY TESTING
(Years)

Road functional class	*Case 1*	*Case 2*
1	35	35
2	35	35
3 & 4	40	35
6 & 8	50	35
7	55	35

TABLE IV.2—INTERIM ROUGHNESS DEFINITIONS OF CONDITION STATES DURING SENSITIVITY TESTS
(counts/km)

Road functional class	*Structural condition*		
	P	$\dot{P}$	$\bar{P}$
1	80	80 to 120	above 120
2	80	80 to 120	above 120
3 & 4	80	80 to 120	above 120
6 & 8	100	100 to 180	above 180
7	100	100 to 180	above 180

on the condition state distributions of Victorian State Highways in 1972 and 1981, all other condition assessment determinants being held constant. If the threshold value changed from 9 years to 8 years, the overall ratio S:S changed from 73:27 to 60:40 in 1972 and from 81:29 to 76:24 in 1981. The condition vectors for the two cases are given in Table IV.4.

CALIBRATION RESULTS

In this study, each approximate transition matrix derived algebraically was iteratively modified by inspection until a matrix judged suitable for condition projections was obtained. The criterion of suitability was that the matrix should predict the observed 1981 state vector from the observed 1972 vector, while simultaneously predicting total 1972–1981 roadwork equal to that recorded by the State road authority. This calibration process amounted largely to adjusting the values of the matrix elements affected by the 'maintenance policy constants'. The extent to which the suitability criterion was satisfied is shown in Tables IV.5 to IV.8.

The lack of absolute accuracy of calibration is thought to be attributable to roadwork being done on roads with sound wearing and sealing courses; and to the assumption of a constant ratio of good to bad geometry in roads deteriorating beyond the SP condition. However, these calculations did approach the limits of computing precision when using six significant figures.

The final transition matrices obtained by this subjective procedure were not unique solutions, but the ranges of matrix element values which gave acceptable calibration were quite confined. Independent check calibrations were conducted and although there were some differences between the check matrix obtained and the accepted

TABLE IV.3—CONDITION STATE VECTORS AT VARIOUS ARS PAVEMENT LIVES 1972

(carriageway.km)

	Condition state number							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
				Legal Class 1 Roads				
Case 1 lives	312	291	171	198	0	115	5	280
Case 2 lives	413	364	181	253	0	4	4	153
				Legal class 2 roads				
Case 1 lives	36	88	128	350	0	12	3	67
Case 2 lives	164	420	11	60	0	1	0	25

TABLE IV.4—STATE VECTORS FOR VARIOUS SEAL CONDITION THRESHOLD VALUES; VICTORIAN STATE HIGHWAYS

Good seal life (years)	*Condition state number*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
				1972 Vector				
8	2966	635	506	1121	236	107	477	341
9	3322	279	813	815	357	202	356	246
				1981 Vector				
8	4132	1321	539	152	88	28	31	6
9	4463	995	574	117	95	28	25	6

matrix the consequences of these differences were small. This can be seen from Tables IV.9 to IV.11 which compare the condition and roadwork projections and pavement lives derived from the accepted transition matrix with those derived from the check calibration matrix.

TABLE IV.5—RESULTS OF TASMANIAN CALIBRATION CHECK; STATE VECTORS

(carriageway.km)

	Condition state number							
Vector	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
				Legal class 1 roads				
Target	272	203	385	219	14	179	3	97
Achieved	273	185	387	225	11	181	3	103
				Legal class 2 roads				
Target	330	216	70	45	0	21	0	1
Achieved	325	215	65	47	4	19	1	3
				Legal class 3, 5 & 6 roads				
Target	64	41	43	12	1	24	0	7
Achieved	61	42	40	12	0	24	0	9

TABLE IV.6—RESULTS OF TASMANIAN CALIBRATION; AVERAGE WORK RATES 1972

(km/year)

	Resealing	*Light reconstruction*	*Bituminous resheet*	*Reconstruction*	*Upgrading*
			Legal class 1		
Reported by SRA	73.8	4.6	12.4	10.0	6.0
Predicted	73.1	4.6	12.0	10.0	6.0
			Legal Class 2		
Reported by SRA	42.1	0	4.2	4.2	0.7
Predicted	42.1	0	4.0	3.9	0.8
			Legal class 3, 5 & 6		
Reported by SRA	8.2	0 2.9	4.0	2.9	
Predicted	7.9	0	2.9	3.7	2.6

TABLE IV.7—RESULTS OF VICTORIAN CALIBRATION; STATE VECTORS

(carriageway.km)

	Condition state number							
Vector	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1981 target	3380	1171	994	279	188	202	61	113
Achieved	3346	1174	1007	290	182	208	68	111

TABLE IV.8—RESULTS OF VICTORIAN CALIBRATION; AVERAGE WORK RATES 1972

(carriageway.km/year)

Work Rates	*Resealing*	*Light reconstruction*	*Bituminous resheet*	*Reconstruction*	*Upgrading*
	Work Types				
Predicted	592.8	0	5.5	62.5	107.4
Reported by SRA	599.4	0	5.4	66.7	114.8

TABLE IV.9—CALIBRATION COMPARISON; PROJECTED 1991 STATE VECTORS

(km)

Transition Matrix Source	*Condition state number*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
			Tasmanian State Highways					
Initial Calibration	238	118	377	232	11	271	4	157
Check Calibration	267	124	393	194	14	255	3	157
			Victorian State Highways					
Initial Calibration	3375	1188	932	262	166	206	61	107
Check Calibration	3426	1197	895	251	161	193	62	111

TABLE IV.10—CALIBRATION COMPARISON; PROJECTED ROAD WORK 1982-91

(carriageway.km)

Transition Matrix Source	*Resealing*	*Light reconstruction*	*Bituminous resheet*	*Reconstruction*[a]
		Tasmanian State Highways		
Initial Calibration	645	47	157	238
Check Calibration	840	50	164	262
		Victorian State Highways		
Initial Calibration	5320	0	33	1621
Check Calibration	5508	0	28	1686

a. Includes reconstruction associated with geometric improvements.

TABLE IV.11—CALIBRATION COMPARISON; PAVEMENT LIVES

(Years)

Transition Matrix Source	*Mean life to reconstruction*[a]	*Standard deviation*
	Tasmanian State Highways	
Initial Calibration	40	25
Check Calibration	38	24
	Victorian State Highways	
Initial Calibration	60	50
Check Calibration	59	50

a. Mean first passage time for the transition state 1-state 8-state 1.

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