



STATENS VÄGINSTITUT · STOCKHOLM
The National Road Research Institute, 114 28 Stockholm, Sweden

CONTRIBUTIONS TO THE DEVELOPMENT OF A
FRAMEWORK FOR MODIFYING THE SWEDISH
FLEXIBLE PAVEMENT DESIGN METHOD

by
T Larson

RAPPORT Nr 108

Stockholm 1970



STATENS VÄGINSTITUT · STOCKHOLM
The National Road Research Institute, 114 28 Stockholm, Sweden

CONTRIBUTIONS TO THE DEVELOPMENT OF A
FRAMEWORK FOR MODIFYING THE SWEDISH
FLEXIBLE PAVEMENT DESIGN METHOD

by
T Larson

RAPPORT Nr 108

Stockholm 1970

FOREWORD

This report is one of two prepared during the writers association with the Swedish Statens väginstitut in the summer of 1970. Mr Nils G Bruzelius, Director of the Institute, outlined the task in a letter of March 11, 1970 (Ref 39-70-0209) in which he suggested that principal attention be given "... to application of the American road design criteria to the design of roads in Sweden". The work was performed under the immediate direction of Mr Olle Andersson, Chief, Road Foundation Department.

The writer had no previous knowledge of the Swedish roads or of the design methods used in that country. Therefore, the two papers are essentially briefing documents for those actually engaged in revising current pavement design procedures. During the course of the summer, however, field trips and personal travel provided an extensive overview of the excellent Swedish road system. Some of the opinions expressed in these papers are based on this limited type of observation.

The professional and administration staff of the Institute were unfailingly gracious and helpful in providing the many kinds of assistance a foreign traveler and worker needs. For everything they have done and for the opportunity to work and live in Sweden I express a very real gratitude.

T Larson
Stockholm, August 1970

CONTRIBUTIONS TO THE DEVELOPMENT OF A FRAMEWORK FOR MODIFYING
THE SWEDISH FLEXIBLE PAVEMENT DESIGN METHOD

CONTENTS

INTRODUCTION

NOTES ON THE ELEMENTS OF A GENERALIZED FLEXIBLE PAVEMENT
DESIGN EQUATION

Performance

Traffic Loading

Environment

Subgrade Strength

Surface, Base and Subbase Strength

A SYSTEMS APPROACH TO THE PAVEMENT DESIGN PROCESS

Examples of the Systems Method

Notes on Implementation

EXAMPLES OF CURRENT PAVEMENT DESIGN PROCEDURES

USA

California

Michigan

Pennsylvania

Asphalt Institute

Summary

Great Britain (based on pending version of Road Note 29)

REFERENCES

CONTRIBUTION TO THE DEVELOPMENT OF A FRAMEWORK FOR MODIFYING
THE SWEDISH FLEXIBLE PAVEMENT DESIGN METHOD

INTRODUCTION

Design procedures serve as guides to the orderly consideration of all relevant aspects of a design problem. Sound procedures can promote uniformly good performance of structures, in both a technical and economic sense. Incomplete or erroneous procedures can obviously promote faulty performance. It is worth noting, however, that either good or bad design guides, tables and so forth may stifle creativity if viewed and used in a dogmatic, rigid fashion.

Though many relatively unsophisticated design procedures have been used in the past to select dimensions for the road pavement structure, it is now obvious that for developed countries the rate of expenditure for new roads and major improvements, the rate of traffic growth and the availability of new materials all suggest a very high order of efficiency in this design process as being required for the future. Unfortunately such efficiency has been elusive, in part for the reason that roadbuilding has been, and continues to be, very much an "art", but also because research and development efforts have not followed a consistent, systematic plan of attack. The problems have been too numerous, too urgent and too multidisciplinary in nature while the research and development efforts have been too fragmented to permit such an approach. It would seem that improved pavement design methods can be developed only within a carefully structured framework. This framework must reflect an awareness of the very rich resources of past road research, treat the unique conditions of actual roadbuilding practice, and have a breadth and flexibility that modern systems engineering makes possible.

The purpose of this paper is to make contributions to the development of a framework such as that noted above for Sweden. It contains a selective review of recent USA (and some other) literature treating principal elements of the pavement design process, some examples of the systems approach to pavement design, and examples of current pavement design procedures. It was felt that in these areas a person with no experience in Sweden might nevertheless offer something of value to the total effort.

NOTES ON THE ELEMENTS OF A GENERALIZED FLEXIBLE PAVEMENT
DESIGN METHOD

The search for a generalized flexible pavement design equation that would show pavement performance as a dependent variable in the form

$$\text{Performance} = f(W, X, Y, Z)$$

where W = loading by traffic

X = environment

Y = subgrade conditions

Z = pavement strength

appears to have been formalized during the AASHO Road Test. However, such a relationship has not been quantified to date and perhaps never will be. Yet it serves as a useful framework for examining various critical areas of the problem (see Fig 1). In the next sections the term of this generalized relationship will be examined with particular reference to recent research and development in the USA.

Performance

A pavement performs properly when it provides a surface over which vehicles can move safely, and as smoothly as passenger comfort and the security of freight goods demands; all at minimum whole-life total cost. Reliable, rational, efficient methods for performance evaluation are an obvious prerequisite to the systematic improvement of pavements and thus of pavement design methods, yet relatively little was done in this area before the AASHO Road Test. There a method for the interpretation of road profile information was developed that has been reported by Carey and Irick (1)^{*}. Since that time much more attention has been given also to road surfaces as they affect road-tire friction and safety. Standards in this area are reviewed by Meyer (2).

The idealized requirements of a flexible pavement performance evaluation system are now known to include the following:

1. High speed operation compatible with traffic flow.
2. Ability to sense several kinds of surface conditions and to produce information concerning general performance and the need for maintenance or reconstruction.

* Numbers in parenthesis refer to attached list of references.

Three fundamental measurements are required in such a system; surface profile, pavement strength, surface friction. No single item of equipment now available will make all of these measurements and the devices used for individual measurements are often not compatible with traffic. However, several types of equipment now under development can be used in a systematic fashion to give the information needed for efficient performance evaluation with minimum traffic interference.

Hveem (3) has described some of the early attempts to devise equipment for measuring road profiles. The critical task, however, is relating some profile index to a measure of passenger comfort and security of transported goods. In the reference given earlier (1) Carey and Irick treat the use of a "panel of experts" to link numerical indices of pavement condition to road user opinion. The CHLOE profilometer was the basic instrument developed to make the user-sensitive performance evaluation measurements.

Hutchinson (4) points out the systematic errors inherent to the "consensus of experts" approach used at the road test in developing the PSI concept. He favours a simple numeric index and suggests measuring decrements in performance of a tracking task by the occupants of a vehicle on the pavement under study. Work at The Pennsylvania State University (5) is aimed at relating GM profilometer output to accelerometer data taken onboard the study vehicle. Either of these approaches can be used for rapid surveys over long stretches of roadway without disrupting traffic. Other profilometers, the BPR roughometer for example, have been correlated with PSI values as determined at the road test for rapid pavement evaluation.

Periodic high speed profile evaluations can tell road administrators where maintenance is required, its relative urgency, and within broad limits, the type of maintenance required. Such measurements obviously can be used in the evaluation of new or revised design methods.

Field determinations of pavement strength have been made by plate bearing, vibratory wave propagation, and beam deflection techniques. All of these are relatively slow, expensive and disruptive to traffic and so should be used to complement profile measurements where more specific information is required than the rapid survey can provide. These techniques are particularly useful in studying the performance of pavements constructed to meet new design specifications since evaluation is possible before traffic induced deterioration becomes significant. The deflectograph described by Prandl (6) and evaluated extensively by Lister at the Road Research Laboratory appears to offer promise as a method that can be used in traffic without special barricades and lane closings. It combines the

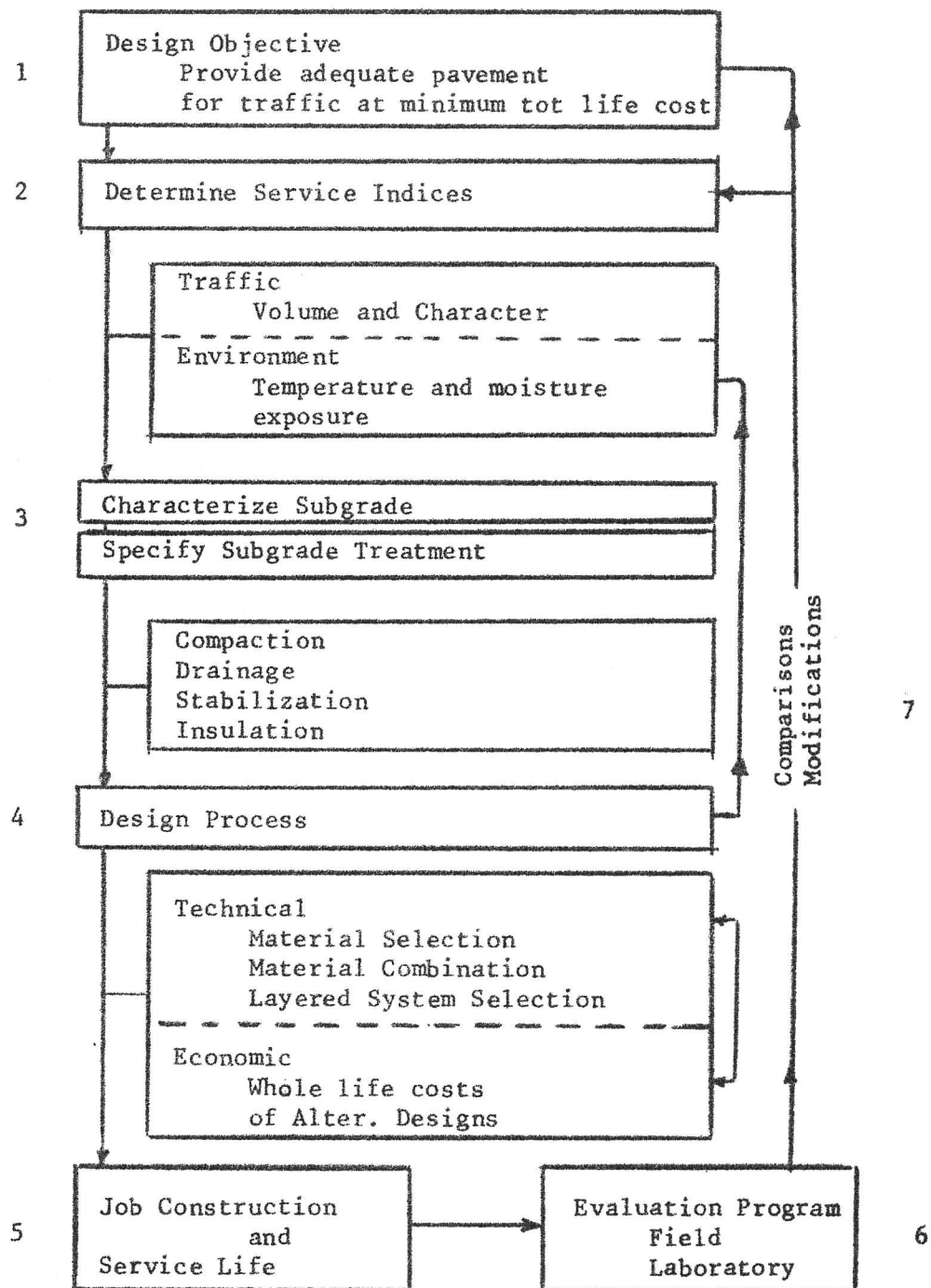


Fig I

widely accepted Benkelman Beam approach with a high speed data acquisition system and uses a truck mounting to make the unit self sufficient, mobile and safe in traffic. It is, however, a static testing device and incapable of measuring the critical dynamic response of flexible pavements.

The third type of measurement required for pavement evaluation is road friction. Loss of friction through surface polishing has come to be recognized as a type of failure just as critical in pavement performance as structural failure. As such, it must be considered in the pavement design process, in the whole-life economic study and methods for measurement must be provided in the systematic performance evaluation process. The SCRIM (Sideways Coefficient Routine Investigation Machine) device developed by the Road Research Laboratory is perhaps a good example of modern high production devices used for this purpose.

To sum up concerning performance, we may say that a program for evaluating pavement performance on a routine, system-wide basis must be available if creative advances in pavement design are to be made. Adequate equipment necessary for making the fundamental measurements for pavement evaluation; profile, strength and friction, now exists but has been in a state of rapid development. For this reason the necessary task of collecting and relating numerical indices to user judgements has been lagging somewhat. Present equipment, however, is at such a state of development that a system can be specified and these tasks undertaken. Such work should have a high priority in the total pavement improvement program. The desire of researchers to produce a unique and perfect tool for their particular investigations should not stand in the way of fuller utilization of equipment now available.

Traffic Loading

There are several approaches to the problem of relating pavements to traffic. These range from traffic-independent on one extreme to traffic-dependent on the other. In the traffic-independent approach the pavement is designed to carry any number of legal loads and deterioration results largely from environmental influences. As the name implies, traffic is considered as the critical element in the traffic-dependent approach. The AASHO Road Test, for example, led to the development of curves relating PSI to load applications (7). As a middle ground pavements may be designed for some ultimate load and numbers of load applications may or may not be considered.

The trend in the US is towards traffic-dependent pavement design methods. The state of California (8) appears to have first used this approach and, as just noted, the AASHO Road

Test did much to promote it. Where the climate is relatively mild, as in much of the USA, a traffic-dependent approach is appropriate and theoretically attractive since the concepts of elasticity can be used to develop numerical indices for the effect of traffic. The typical mixed traffic spectrum can be converted to equivalent wheel load of some standard value by the application of appropriate constants.

Extensive pavement performance data from the state of Michigan (9) where the climate is quite severe tends to support the traffic-independent approach. Similar data has been gathered in Canada (10). Although climate provides one explanation to these apparently anomalous situations (anomalous with respect to the AASHO Road Test for example) other and perhaps more subtle factors also exist. In regions where frost is a major factor in pavement performance the design methods have evolved from experience with severe failures. The most common approach to solving such failure problems has been the use of thicker layers of frost free materials. Such materials characteristically have excellent bearing capacity and so traffic influences are minimized; albeit, indirectly.

Michigan has long based its pavement design on pedological soil classes and has concurrently had an extensive pavement evaluation system. In combination these have tended to produce failure free and hence traffic-independent pavement. For the future, however, new methods of preventing frost penetration and the ineconomies of failure free design may conspire to bring changes in this approach.

Before leaving the issue of road traffic two other points deserve attention: The growth in traffic, particularly truck traffic and the accommodation of very heavy loads on highways. According to Jonsson (11) the ton-km increase in truck transportation in Sweden for the period 1950-66 was not less than 12 % per year. Similar growth rates in this industry are common in highly developed countries. The question for the designer is how to estimate the traffic that a pavement must carry over its design life of perhaps 20 years. No adequate answers to the question have been found but the following points should be noted:

1. As motorways develop they tend to channelize truck traffic.
2. Changes in legal limits or in permit operation can drastically alter the load spectrum.
3. Traffic growth must not be projected beyond the capacity of the roadway.
4. Stage construction offers a conservative approach to the traffic growth problem.

Many very heavy loads, loads well above legal limits, move over the highway system. Most countries use a permit scheme to control such traffic. The effect of this traffic on pavements has been studied in detail by Van Vuuren (12). He presents a rational method based on equivalent wheel load concepts for calculating the effects of very heavy loads.

It appears, then, that traffic-dependent pavement design is gaining favour in regions of mild climate and might do so in the future in northern regions. In any climate, however, the relationship between traffic loads and pavement performance depends on the design methods used and therefore extrapolations can be made only in specific situations and then with extreme care. For example, the AASHO Road Test reports clearly warn against using the PSI versus load application relationships for other than the specific conditions that existed at that road test. The gathering of loadometer data and the development of ESWL factors and methods of treating mixed traffic loads should be part of the development of any forward looking pavement design procedure.

Environment

There is a rather curious trend in the USA towards disassociating flexible pavement design and environment. This trend is curious since such a disassociation is not suggested by the evidence from the WASHO and AASHO Road Tests and from most practical experience. The treatment of the pavement structure as a separate entity is perhaps best characterized in the most recent edition of the Asphalt Institute's Thickness Design Manual (13). Here they note that properly designed full depth asphalt pavements are adequate for the reduced strength subgrades in the spring thaw period. All other frost problems are left to the discretion of the engineer.

In the USA, northern states commonly estimate frost penetration based on some freezing index and use this to specify minimum pavement thickness. Work by the US Army Corps of Engineers (14) has long been used as the basis for this approach.

Work by the British Road Research Laboratory, reported in LR 90, describes a test for the frost susceptibility of soils. It gives general conclusions concerning the likelihood of frost heave for various types of roadbuilding materials in the UK. These conclusions form the basis for the treatment of the frost heave problem in Road Note 29, the British pavement design method.

Currently the use of insulating materials and coloured paving materials is being studied as a means to control frost penetration. Typical of such work is that under way at Purdue and Clarkson Universities and the Alaska Dept. of Highways.

In his paper concerning a pavement design framework Hutchinson (10) suggests the possibility of using relatively coarse classes of environment for pavement design. He suggests the following:

Drainage classes	- Good, Imperfect, Poor
Rainfall classes	- 30" per year, 40" per year
Freezing Index classes	- less than 1000 degree days
	1000 - 1500
	1500 - 2000
	2000 - 2500
	more than 2500

In Appendix A of Hutchinson's paper there are plots of performance rating-age trends for the various environmental classes. This work is not exhaustive but it does offer a reasonable approach. The environment indices can reflect differences within a country and also developments in insulating and drainage technology.

In the USA there is a growing and long overdue awareness of how little is known of pavement microclimates. Current work by Straub (Clarkson), Marshall (U. of Illinois), Bernie, Cady (Penn State University) and others is aimed at closing this knowledge gap through use of improved instrumentation, computer simulation and transferral of working technology from the physical and agricultural services. Meanwhile engineers contrive to use experience based minimums to account for extreme climates even while their technical and economic adequacy are being questioned.

Subgrade Strength

In current USA pavement design practice one finds that in most cases subgrade strength is treated in an empirical fashion. Undoubtedly the best known example of this empirical approach is the CBR method, first described by Porter (15). This method evolved as many observations of pavement performance on soils with varying CBR values were organized into pavement design curves. The curves relate wheel load and the total

thickness of pavement (bituminous surface and granular unbound base) to the subgrade CBR values.

The simple empirical approach to subgrade strength evaluation, and the whole design process, typified by the CBR method, has much to recommend it. Perhaps most important is the fact that it permits an easy accommodation of experience which often is embarrassingly inconsistent with theory. Furthermore solution charts and nomographs, free of impossible looking equations, can be developed for routine use. Finally to some engineers the heterogeneous nature of subgrade materials seems to defy and even render nonsensical rigorous treatments based on elastic or plastic theory.

It is not the purpose of this paper to explore in depth the merits of empirical versus theoretical treatments of subgrade strength. However, it must be pointed out that Peattie (16), Dormon and Edwards (17) and others who favour a fundamental approach to the design of flexible pavements seek, for reasons of convenience, to relate the elastic constants of soils to the CBR. It seems obvious that at present the CBR is the most widely recognized index of subgrade strength. At one time or another it has been correlated with almost every other soil strength index.

Since the laboratory version of the test is essentially a confined compression evaluation, CBR results are a standardized measure of soil strength. As with most tests, the quality of the results depend on very strict observance of arbitrary rules and procedures that constitute the method. The test tends to give more consistent results on fine grain soils than on gravelly material due to the relatively small specimen size. Nevertheless its popularity is evidence that the procedures are relatively simple and flexible and that CBR results have been found meaningful for a wide range of subgrade types and conditions. Detailed studies of this method are reported by the US Army Engineers (18).

CBR tests are made in both field and laboratory. The laboratory procedure is attractive in that moisture and consolidation effect can be varied in an attempt to predict the critical conditions for a soil. However, the problem of how well the laboratory test predicts the critical field CBR has not been entirely resolved. Shook and Finn (19) determined that at both the AASHO and WASHO road tests laboratory CBR values did reasonably predict field CBR values taken at various times throughout the test program. They also note that after approximately 1 1/2 years of testing and two spring thaw periods moisture content and density of the AASHO test road subgrades were not significantly changed from the as-built values.

Subgrade strength was not included in the AASHO Road Test as a major variable. Rather, a program of satellite tests was recommended to extend the AASHO concepts to regions with other soils and climatic conditions. (Many extrapolations and extensions of the AASHO findings have been made without due consideration of this clearly stated limitation.) But the principal method of measurement of subgrade strength at the road test was the California Bearing Ratio and Shook and Finn (19) have used these test data in their development of design equations from the road test.

In regions having predominantly transported soils, the pedological soil classification system has been used extensively as an indicator of subgrade strength. Keyser (20) describes how a flexible pavement design method for the state of Wisconsin was developed on the basis of pedology. While the pedological soil classification system is based on agricultural aspects and needs, there has been a great deal of work (much of it reported by the Highway Research Board) that shows that highway performance also can be predicted on the basis of this classification system. The great advantage of this approach in the USA derives from the fact that soil scientists have prepared detailed maps, using an air photo base, for large portions of the country.

Keyser explains the process of selecting 124 major soil series units to describe engineering performance. He prepared a set of semiempirical pavement design curves based largely on the Group Index, CBR and Corps of Engineers methods. These curves were checked by detailed performance studies of 300 miles of flexible pavements. Soil samples from the study sections were classified according to the new soil series system. While the first design curves had pavement depth as ordinates and Group Index and CBR as the abscissae, the final versions use as abscissae a subgrade Pavement Design Index (PDI) based on frost susceptibility, physical properties, topographic position, pedological horizon, geologic formation and mode of deposition, and internal and external drainage. Each unit in the 124 soil series classification system was then assigned an appropriate PDI value. Following this, pedologic maps could be used as a basis for design with a minimum of field or laboratory work since the science of pedology is founded on the principal that the same soil unit in this classification system will behave similarly wherever it is found.

In summary, the importance of proper evaluation of subgrade strength as a part of the pavement design process cannot be overemphasized. Much of the US practice centers around the CBR test method except in the northern states having largely depositional soils. Here pavement design is based on the pedological soil classification and performance studies. Even

here, however, the CBR test is often used to assist in judging subgrade strength.

Surface, Base and Subbase Strength

There is substantial agreement that the elastic multi-layered model is appropriate for relating loads to stresses and strains and hence to pavement dimensions. Using this model, flexible pavements may be viewed as a combination of bonded and unbonded layers resting on a semi-infinite layer of soil. Critical points in the system include the bottom of the bitumen bound surface layer (horizontal tensile stress), and the top of the subgrade (vertical compressive stress), both measured directly under the wheel load.

Papers supporting the elastic layered approach to pavement design were presented at both the first and second International Conferences on the Structural Design of Asphalt Pavements (16, 17). There are, however, ways in which this basic model is inadequate and inappropriate, particularly in the view of design engineers. (Also to the theoretician concerned with rheology and viscoelasticity.) It is for this reason perhaps that virtually all working design methods in the US are empirical.

The use of available theory and the continued search for better theoretical models of flexible pavements can be justified nevertheless on the basis that new materials and configurations of materials and new loadings will be used in the future and because economy in road construction is being considered more carefully than in the past. Empirically developed pavement design methods are by definition less amenable to innovation in either a technical or economic sense than those based on theoretical concepts.

In this section some general comments will be made on the AASHO based empirical and the elastic layered methods for pavement design.

At the AASHO road test charts were developed for determining pavement thickness on a specific subgrade and for a given traffic spectrum. There are numerous reports in which various states of the US describe using AASHO test results to revise their empirical flexible pavement thickness design methods. A report by Kersten and Skok (21) provides a good illustration of this process in the state of Minnesota.

Since 1954 Minnesota had specified flexible pavement thickness in terms of AASHO soil classification, ADT and HCADT (heavy commercial ADT), a specified maximum spring season axle load, and gravel equivalent factors. (All rather similar to the

present Swedish Method.) It was decided to study possible revisions using 50 test sections selected from in-service highways. The test sections included widely varying dimensions for surface, base and subbase layers, a variety of soils, and ranges in both traffic and climate. All test sections were of modern design and construction.

On these sections tests and measurements were made to characterize the soil (CBR, California R and triaxial tests), to determine strength (plate bearing and Benkelman beam tests), to determine PSI (the BPR roughometer was used) and to characterize the traffic (equivalent 18,000 lb loads were calculated). Measurements of strength and PSI were continued over several years with particular attention given to the spring thaw periods.

Results of this program included the following:

1. It was recommended that a strength measure be adopted as a criterion for subgrade classification since the AASHO classification in use was not sensitive enough to permit the efficient choice of pavement structure. Specifically the California R test was recommended on the basis of performance and ease of operation.
2. The gravel equivalency approach to thickness design was not changed but equivalency factors for some types of construction were modified. (Changes ranged from minus 8 in. to plus 2 in.) The old factor for hot-mix asphalt of 2.25 was verified and recommended for continued use.
3. It was recommended that a traffic factor be calculated based on equivalent 18,000 lb loads. It was felt that this would be more realistic and more sensitive to change than the HCADT classification).
4. From the serviceability ratings of the test sections and the various strength and performance measures it was found that pavement life could be predicted most reliably and simply using Benkelman beam spring deflections.

The Minnesota experience illustrates a well planned and executed program for updating an empirical pavement design method. In particular it demonstrates how much time and field experimentation are required to change an empirical method. Observation of the test section and of new pavements will continue so as to further verify the recommended changes.

Baker (22) has presented the following useful observations on the elastic layered system approach to pavement design:

1. Elastic theory provides the simplest, most reliable basis for approximating the behaviour of many structures. Judgement and experience must complement it since materials are not perfectly elastic and since environment and load conditions defy accurate prediction.
2. Values of the elastic modulus and Poissons' ratio are critical in the Burmister layered theory approach since they describe the load distribution capability of a material. It is important to evaluate the materials properties on a time-dependent basis since asphaltic concrete exhibits completely different behaviour under moving loads as opposed to static ones.
3. The ultimate in theoretical analysis will be achieved when stresses in viscoelastic layered systems can be analyzed. (See Barksdale and Leonards (23) for an example of progress in this area.) Concerning the further development and use of theory, Baker notes philosophically that the very low margin for error (high factors of safety) permitted for pavements has greatly hindered the use of conventional structural design procedures. Only through a realistic approach to safety factors can progress be made in the use of theory for developing working methods of pavement design. Meanwhile empiricism, unexplainable failures and an unknown condition of economic gain or loss will continue.

Regarding pavement strength, it might be said in summary that pavement design in the US relies on time tested empirical methods now being updated using AASHO test results. The non-acceptance of purely theoretical procedures has been ascribed to a preoccupation with designing failure free pavements. Meanwhile many researchers are recognizing economic and technical reasons, similar to those given earlier in this paper, why theoretically based methods capable of giving mathematical substance to the equation posed earlier are vitally needed.

A SYSTEMS APPROACH TO THE PAVEMENT DESIGN PROCESS

The methods of systems engineering have been used extensively and successfully to deal with complex problems in many technical

areas. Only recently, however, has the applicability of this approach been considered with respect to the problem of pavement design. Developing a framework for modifying an existing design method can be viewed profitably as a systems problem. Therefore, recent contributions to this aspect of pavement technology will be reviewed.

Contributions to the Systems Method

Hutchinson (10) has formulated a general design approach for highway pavements. The framework he suggests includes five phases; problem definition, solution generation, solution analysis, optimization and evaluation. When implemented it would permit evaluations of any pavement system, including totally new ones, particularly with respect to their economic characteristics.

In developing a systems approach for a previously unsystematized problem the matter of definition is especially important. Hutchinson suggests the following steps for this phase:

- (a) objectives
- (b) input factors
- (c) output factors
- (d) cost function
- (e) decision criterion and
- (f) constraints.

Highway pavement objectives include providing an adequate serviceability over the design life and minimizing expenditures. Input factors include all things that contribute to serviceability decrements such as wheel loads, climatic factors, subgrade characteristics and so on. He suggests a coarse classification system for input factors. Output is structured in terms of three parameters; pavement serviceability, the serviceability level at "failure" and the age at which this occurs. Failure age is the item to be predicted for each pavement strategy under any given classification of environment.

A cost function relates output to the design objective - - serviceability at minimum cost. Hutchinson suggests the following cost function:

$$AC = CRF_L \left[C + E_1 (PWF_A) E_2 (PWF_{A_r}) - \left(1 - \frac{Y}{X} \right) (E_1 \text{ or } E_2) PWF_{A_r} \right] + M$$

in which:

AC = annual cost of a 2 lane length of pavement and shoulders

CRF_L = capital recovery factor for a design life L and a specified interest rate

C = initial cost per length

A = failure age of the initial pavement (years)

A_r = failure age of first resurfacing measured from the time of original construction (years)

PWF = present worth factor for A or A_r years at specified interest rate

E_1 = first resurfacing cost

E_2 = second resurfacing cost

y = number of years from time of last resurfacing to the end of the design life period i.e. (L - A or A_r)

x = estimated life of last resurfacing

M = average annual maintenance cost per mile

The decision, then, is simply to select that pavement strategy with the minimum expected annual cost. Constraints to this process are identified as establishing some "failure" level of serviceability, determining the interest rate to use and setting some maximum acceptable annual cost for the pavement.

Two broad classes of potential solution are described in detail. These pertain to:

(a) standard pavement strategy - flexible and rigid

(b) new pavement strategy

For standard flexible pavements, of principal concern here, Hutchinson presents data relating various thicknesses of "standard" pavements to failure age and proceeds to illustrate an annual cost curve. The AASHO relationship between various layers

$$D = 0.44D_1 + 0.14D_2 + 0.11D_3$$

where:

D = thickness index

D_1 = surface course thickness

D_2 = base course thickness

D_3 = subbase course thickness

is suggested as a means for developing specific dimensions for the component layers.

Hutchinson suggests using the Road Research Laboratory profilometer to measure pavement serviceability. He also suggests that thickness-deflection relationships for various pavement structures could be developed to describe performance. He further states that a pavement management system should be capable of providing the following information for each environmental class:

- (a) performance history of various designs
- (b) structural properties, material properties
- (c) cost data
- (d) a computer routine for the desired analysis

Lemer and Moavenzadeh (24) have also described an integrated approach to the pavement design problem. They argue that only through use of orderly and well-documented approaches to design will the pavement field be able to keep pace with a rapidly expanding engineering technology. Their methods are generally similar to those described by Hutchinson but are not given the same high level of detail and so will not be described further here.

Burt (25) argues that pavement design methods must be brought to a level of sophistication similar to that which exists in other civil engineering design field. He feels that full scale road tests, the principal bases for present UK pavement design, are slow, expensive and limited by their empirical nature. The systematic program of research at RRL that will provide the necessary theoretical background is described in broad outline form.

Notes on Implementation

Research can describe a pavement design framework, can provide specific inputs to the model under consideration, but only the public highway administration has the resources and the long concern for the problem necessary to make real progress in establishing a modern pavement management system. Ontario, Canada has perhaps the only program which approximates such a system and it has come about there through the efforts of competent researchers, enlightened highway administrators and the cooperation of various highway interests. (e.g. Canadian Good Roads Association) Without this type of cooperation, efforts in any country to change pavement design practice are difficult, and a truly creative change is impossible. It is incumbent on highway researchers supported by public funds to be aware of this fact and to direct a portion of their energies accordingly.

EXAMPLES OF CURRENT FLEXIBLE PAVEMENT DESIGN PROCEDURES

Pavement design must be rather "situation specific" and so there is little to be gained from numeric comparisons among existing procedures. Rather, the general design philosophy, evidences of unique influences and overall effectiveness should be studied. Such an approach will be taken in this section using the current flexible pavement design procedures from several countries. Some notes on the Swedish method are made for comparison and reference purposes.

The Swedish design table for roads appears to have been drafted to provide a certain minimum standard in a country where frost problems have been of paramount importance and where good road building materials have been relatively plentiful. Under these conditions traffic has not been a dominant influence and only very general soil classifications have been used. The Swedish design methods have been effective on the basis of their providing a relatively failure free road construction. It may well be, however, that rapidly increasing volumes of truck traffic, new methods for providing frost protection with attending thinner pavement structures, improvements in pavement technology, material shortages and the need for greater economies in road building are among the factors justifying the need for modification of this design procedure.

USA

Different design procedures are in use by various states of the USA. In part this reflects local environment and conditions but it also reflects on the level of industrial development and technical sophistication.

California

Clearly California has been a leader in developing its highway system and in contributing to highway technology. In 1948 Hveem and Carmany (8) set forth the principals that continue to serve as the basis for the California pavement design procedure. Modifications thru 1962 and an analysis of this method in light of the AASHO road test have been described by Hveem and Sherman (26). From the first, California has based its pavement design method on empirical relationships developed from laboratory research, test tracks and other pavement experiments rather than on mathematical formulations.

The California design method (27) contains factors for the supporting power of the soil, for traffic and for the slab strength of the pavement and base layers. Soil supporting power is based on a test for shearing resistance to plastic deformation of a saturated soil at a given density. This resistance, termed R, is measured by the stabilometer test. (California Test Method No. 301) Mixed traffic is converted to equivalent 5000 lb wheel loads by load equivalency factors. Loadometer studies have led to the development of EWL constants for various types of vehicles and for various classes of highways so that traffic load data can be readily developed for each project.

A traffic index is calculated as

$$T.I. = 6.7 \left(\frac{EWL}{10^6} \right)^{0.119}$$

and used in the subsequent design charts and tables. The required thickness of the pavement layers is expressed in terms of gravel equivalents and calculated as $G.E. = 0.0032 (T.I.) (100-R)$. The general form of this equation was set in 1948 based on test track results. Changes in the coefficient have been made on the basis of other research work. Various flexible paving materials have different gravel equivalent thicknesses for various traffic index numbers. Different combinations of materials are then permitted so as to permit economy in first cost and future maintenance.

This design method has been developed by consistently following an empirical approach in a region very unlike Sweden where most roads are not subject to frost conditions and where the soil is largely residual. After the more than 20 years of use, a very extensive amount of experience now compliments and justifies this method. The AASHO road test results also have been used to validate it.

Michigan

Michigan has soil and climate that are somewhat similar to those of Sweden and so it is perhaps not surprising that their pavement design methods are also similar. (28) Michigan considers that soil conditions and environment are the dominant factors in pavement performance. Housel (9) has shown that all Michigan pavements suffer a cumulative increase in roughness (decrease in PSI) due to effects of climate and soil type and largely independent of traffic. The Michigan design method therefore intends to relate pavement dimensions to environment and so provide a structure capable of carrying legal axle loads at all seasons without damage due to load repetitions. The principal adjustments to dimensions are made in the foundation. Pavement layers are standardized and of nominal thickness.

Most Michigan soils are transported; glacial tills, moraines and outwash areas. Soils are classified and mapped according to pedological class. Within each class laboratory tests, CBR for example, and field performance data have been accumulated. Therefore pavement design can be accomplished by identifying the foundation soil and using a previously validated set of dimensions.

The role of field performance studies in this procedure deserves particular emphasis. The Michigan Highway Department has had a very extensive Cooperative Pavement Performance Study with the University of Michigan and the US Bureau of Public Roads since 1946. Only by this means has the performance expectations of various soil classes been kept current with respect to traffic and pavement technology. Pavement profile measurements are the principal criteria for evaluating pavement performance (29).

Pennsylvania

The pavement design method used by the state of Pennsylvania (30) is a composite one based on the AASHO test, on experience and on The Army Corps of Engineers frost penetration data (14). Pennsylvania has a very extensive state controlled highway system and is an E-W corridor state with heavy industry and very heavy truck traffic. Crushed stone has been plentiful and cheap in much of the state so crushed aggregate bases have a long service history. The regions of folded and tilted rock formations, together with those having glacial depositions, often cause erratic subgrade conditions. The climate is severe (1400 - 1500 Freezing Index in the North, measured as the maximum ordinate on a plot of degree days, algebraic difference between average daily temperature and 32°F, versus time).

The Pennsylvania procedure specifies a minimum pavement structure depending on the class of highway, the pavement type and the freezing index. This requirement is based on a modification of US Army Corps of Engineers EM-1110-1306. By this treatment flexible (layered system with untreated base course), and modified flexible pavements (flexible pavement systems with chemically strengthened bases) are protected from frost harm and spring strength reduction. Given frost penetration (as calculated by EM-1110-1306) a frost penetration diagram is used to determine the minimum total penetration thickness.

Subgrade soil bearing capability is determined by CBR (AASHTO 193-63). A minimum CBR value of 3 is normally used for projects when fill material will be imported. The design CBR may be increased by subgrade treatment.

Traffic is considered by calculation of an 18 kip daily single axle load equivalent from traffic counts and average truck weight data. Traffic counts are made for the road corridor and expanded to cover the estimated total life of the project.

Pavement thickness is taken from a design nomograph developed from AASHTO results and Pennsylvania experience which relates CBR and equivalent daily 18 kip traffic to a structural number (an index number of total pavement thickness). Various materials may be used to provide the required structural number according to the formula

$$SN = A_1 D_1 + A_2 D_2 + A_3 D_3$$

where A_1, A_2, A_3 = coefficients of relative strength

D_1, D_2, D_3 = thicknesses of surface, base and subbase, respectively

Minimum values for D_1, D_2, D_3 are specified for different highway classes, traffic volumes and material types based on experience.

The Asphalt Institute

The Asphalt Institute has recently published the eighth edition of its guide to thickness design of asphalt pavements (13). This edition of the manual clearly emphasizes pavements comprised entirely of asphalt concretes.

Pavement thickness is determined from design charts which consider subgrade strength (CBR, plate bearing, or R), and a traffic index. These design charts have been developed empirically and are based largely on AASHO and previous road test results. Much of the detailed background for the present thickness charts was developed by Shook and Finn (19).

Concerning environmental effects, the following is quoted from the manual:

"The three most critical (environmental) factors are moisture, soil expansion and frost effects. CBR and R-value methods both take into account the critical effect of strength loss due to saturation and swelling of the soils. But effects of these factors must be estimated for the Plate Bearing Test because it is made in place.

Frost action can be evaluated on the basis of either frost heave or weakening during the frost melting period. The design method of this manual takes into account reduced supporting capacity of the subgrade during the frost melt period. Abrupt changes in subgrade conditions and local areas where soils are highly susceptible to frost heaving and frost boils should be removed and replaced or reworked to unify the upper portion of the subgrade."

This new asphalt institute method, recommended for the widely varying condition over the entire USA permits dimensioning a slab of asphaltic concrete much as Portland cement concrete slabs have long been dimensioned. It does not treat the problem of foundation preparation except through a strength index number. This approach brings an attractive rationality to flexible pavement thickness determination; given a load spectrum and a support value, it uses elastic layered theory and experience to find the thickness of uniform asphalt concrete required. It is somewhat early to judge the efficiency of this approach although there has been a report covering extensive tests in Canada (31).

Summary of USA. Examples

Several observations on USA flexible pavement design methods now will be drawn from the above examples and the writers experience. It should be carefully noted that this is not intended to be a numerical comparison of pavement dimensions obtained using the various methods nor of theoretical research pertaining to flexible pavements. Rather it is an examination and comparison of several working procedures.

1. Since the AASHO road test there has been a trend towards designing pavements on the basis that over time a given traffic loading will "use up" their effective life. This is usually measured by a change in PSI. Such a "rational" trend requires increased attention to traffic and loadometer data and the use of relatively standard pavement materials or an agreed upon system of material equivalents.
2. It would be difficult to identify the true theoretical basis for most pavement thickness design methods now in use. Where theoretical values existed they have been modified to conform to road test results and minimum values based on experience. Nomographs, graphs or tables are provided for use by design engineers.
3. The Asphalt Institute has made a significant departure from most state practice through emphasis on full depth asphalt concrete designs. This approach emphasizes the use of a single high quality bitumen bound concrete to replace the layers of different materials formerly used. In many ways it is similar to the rigid pavement design concept where almost complete emphasis is given to the principal paving material in the recommended design guides.
4. The state of Michigan approaches pavement design as a foundation problem and uses minimum pavement thicknesses that have been developed from long experience. Very extensive pavement evaluation data from Michigan suggests that when pavements are designed and constantly adjusted to preclude traffic failures then soil and climate, rather than traffic, are the principal factors effecting the change in pavement serviceability.
5. The actual dimensions of pavements in the USA has not changed rapidly in spite of massive research programs and road tests and are unlikely to do so in the future. This is because virtually all methods now rely on empirical relations and observation of performance. The principal change over recent years has been the rather wide acceptance of
 - a) the serviceability concept and
 - b) the "structural number" approach to thickness design with virtually unlimited alternative combinations of surface, base and subbase layers on the basis of thickness equivalences.

Great Britain

The British road design procedure is given in Road Note 29. This document was first published in 1960, was revised in 1965 and has now been updated for official release in the Fall of 1970. Comments in this section are based on the new version and so far the present are unofficial except where they correspond to material given in the 1965 edition.

England has extremely dense and heavy traffic, and, in general, poor road building soils and high water contents. Frost penetration, however, is light. (18 in. the common maximum) The Road Research Laboratory, has guided the development of pavement design to meet these conditions through the use of extensive full scale road tests. Thus pavement design is an empirical process that changes in an evolutionary fashion.

In the new pavement design procedure traffic is defined in terms of the cumulative equivalent 8200 kg (18,000 lb) axle loads. Pavements are designed to carry some number of "standard" axles during the design life of the project. Load equivalency factors are essentially those developed at the AASHO road test. Only truck traffic (unladen weight exceeding 1500 kg) is considered and it is estimated in the following sequence;

- (a) use a traffic census to determine present truck traffic in each direction
- (b) use growth curves (provided for 3, 4, 5 or 6 % annual rates of increase) to find total vehicles
- (c) for the class of road use factors to give average number of axles per truck and "standard" axles per commercial axle.

Drainage and frost penetration are treated as the relevant environmental factors. It is recommended that in all cases the water-table be prevented from rising to within 600 mm of the subgrade surfaces through use of sub-soil drainage or embankments. Frost susceptible soils are described in an appendix to the method. No frost susceptible materials may be used within 18 in. (450 mm) of the surface.

The CBR test is used to specify subgrade and subbase strength. Subbase thickness is specified by curves relating CBR, total traffic and thickness. The laboratory CBR procedure is recommended, using the density and moisture conditions likely to occur in service.

Base and surface thicknesses vary with the type of material used and with total traffic. The surface course may be delayed

to permit traffic compaction of base courses in certain circumstances. In general, stage construction of flexible pavements is favoured on an economic basis. In every case minimum thicknesses related to local conditions are given for all pavement layers.

The full document gives flexible and rigid pavement design methods. It also gives a method based on equivalent wheel loads for designing roads for concentrated industrial traffic. All aspects of the design process are fully explained and illustrated and with the recent updating it is perhaps the most current and explicit empirical design procedure available.

REFERENCES

1. W.N. Carey and P.E. Irick, "The Pavement Serviceability Performance Concept", Bulletin No. 250, Highway Research Board, 1960.
2. W. Meyer, "Tentative Skid Resistance Requirements for Main Rural Roads", National Cooperative Highway Research Program Report 37.
3. F.N. Hveem, "Devices for Recording and Evaluating Road Roughness", Bulletin No. 264, Highway Research Board, 1960.
4. B.G. Hutchinson, "The Measurement of Highway Performance", Proc. 2nd Conference on the Structural Design of Asphalt Pavements, 1967.
5. A. Brickman, et al, "On Developing Pavement Performance Indices Using the GM Profilometer", Unpublished Reports to the Pennsylvania Department of Highways, 1968, 69.
6. E. Prandi, "The Lacroix L.C.P.C. Deflectograph", Proc. 2nd Conference on the Structural Design of Asphalt Pavements, 1967.
7. "The AASHO Road Test - Pavement Research", - Highway Research Board Special Report 61-E, 1962.
8. F.N. Hveem and R.M. Carmany, "The Factors Underlying the Rational Design of Pavements", Highway Research Board, Proceedings, Volume 28, 1948.
9. William S. Housel, "The Michigan Pavement Performance Study for Design Control and Serviceability Rating", Preprint Volume Supplement, 1st Conference on the Structural Design of Asphalt Pavements, 1962.
10. B.G. Hutchinson, "A Design Framework for Highway Pavements", Ontario Joint Highway Research Programme Report No. RR127, Ontario.
11. R. Jonsson, "Den Tunga Lastbilstrafiken", Statens Vägverk, TÖ103, 1969.
12. D.J. Van Vuuren, "The ESWL Concept and its Application to Abnormally Heavy Vehicles on Roads", Civil Engineer in South Africa, Volume 11, No. 8, 1969.
13. "Thickness Design, Full Depth Asphalt Pavement Structures for Highways and Streets", The Asphalt Institute Manual Series No. 1 (MS-1) Eighth Edition, December 1969.

14. "Engineering and Design, Pavement Design for Frost Conditions", US Army Engineers EM-1110-345-306.
15. O.J. Porter, "Foundations for Flexible Pavements", Proc. Highway Research Board, Volume 22, 1942.
16. K.R. Peattie, "A Fundamental Approach to the Design of Flexible Pavements", Preprint Volume, 1st Conference on the Structural Design of Asphalt Pavements, 1962.
17. G.M. Dormon and J.M. Edwards, "Developments in the Application in Practice of a Fundamental Procedure for the Design of Flexible Pavements", Proc., 2nd Conference on the Structural Design of Asphalt Pavements, 1967.
18. "The California Bearing Ratio Test as Applied to the Design of Flexible Pavements for Airports", Tech. Memo. No. 213-1, US Army Engineers, 1945.
19. James F. Shook and Fred N. Finn, "Thickness Design Relationships for Asphalt Pavements", Preprint Volume, Conference on the Structural Design of Asphalt Pavements.
20. R.H. Keyser, "The Application of Pedology to Flexible Pavement Design in Wisconsin", Preprint Volume, 1st Conference on the Structural Design of Asphalt Concretes, 1962.
21. Miles S. Kersten and Eugene L. Skok, Jr, "Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota", Highway Research Record No. 291, Highway Research Board, Washington, D.C., 1969.
22. Robert F. Baker, "A Structural Design Procedure for Pavements", Preprint Volume Supplement, 1st Conference on the Structural Design of Asphalt Pavements, 1962.
23. Richard D. Barksdale and G.A. Leonards, "Predicting Performance of Bituminous Surfaced Pavements", Proceedings, 2nd Conference on the Structural Design of Asphalt Pavements, 1967.
24. A.C. Lemer and F. Moavenzadeh, "An Integrated Approach to Analysis and Design of Pavement Structure", Highway Research Record No. 291, Highway Research Board, Washington, D.C., 1969.
25. M.E. Burt, "Research on Pavement Design", Road Research Laboratory Report LR243, Crowthorne, England, 1969.

26. F.N. Hveem and G.B. Sherman, "California Method for the Structural Design of Flexible Pavements", Preprint Volume Supplement, 1st Conference on the Structural Design of Asphalt Pavements, 1962.
27. "Structural Design of the Roadbed", California Planning Manual, Part 7 - Design, Section (7 - 600), Sacramento, California, August 30, 1968.
28. "Field Manual of Soil Engineering". 4th edition. Michigan State Highway Department, Lansing, Michigan. 1960.
29. William S. Housel and O.L. Stokstad, "Pavement Profile Surveys to Correlate Michigan Design Practice with Service Behaviour", Highway Research Board Proceedings, Volume 38, 1959.
30. The Pennsylvania Department of Highways, Pavement Design Manual, Paragraphs, 2.14.03, 2.14.24, 2.14.34 and Appendices A, B, C, D, Harrisburg, Pennsylvania, 1968.
31. W.A. Phang, "Four Years Experience at the Brampton Test Road", Ontario Highways RR153, Ontario, 1969.

