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DETERIORATION AND RELIABILITY OF PAVEMENTS, (U)
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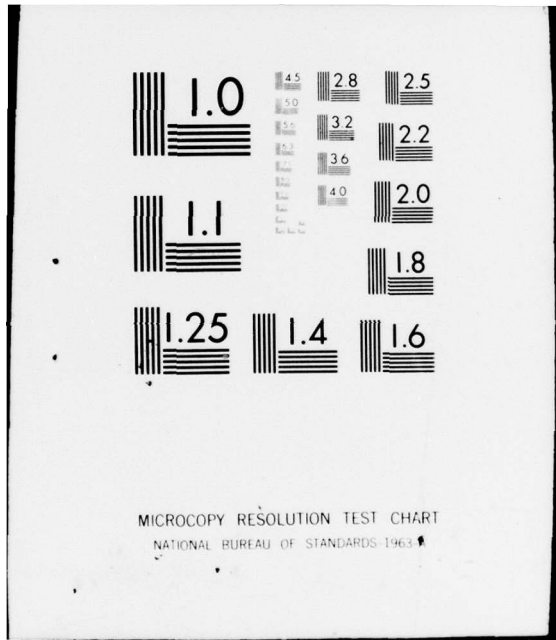
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PART I: INTRODUCTION

Pavement design has traditionally been set apart from maintenance and repair considerations. Early design procedures, by omission, presumed that pavements performed some service up to a point where sudden failure occurred as a result of some predetermined quantity of traffic. This "failure" was some finite definition of the pavement condition. However, it has been intuitively obvious that the pavement deterioration, or damage, occurred upon initiation of traffic and gradually increased to some point where conditions were unsatisfactory. It was also obvious to the designer that this unsatisfactory condition varied from one facility to another depending upon the needs and desires of the user.

More recently, members of the pavements community of engineering have sought after methodology for quantifying deterioration of pavements in various modes and for more properly quantifying failure of a pavement. These achievements have been considered essential to obtain the highest possible benefit from a pavement throughout its entire life. This concept has been termed "life-cycle management," which can be described as the management of a pavement from its conception to the end of its life. The term then should include planning, design, maintenance, repair, and some control of usage.

In order to effect life-cycle management, essentially every trade-off must be optimized. Particularly, a design must be at minimum cost with respect to deterioration. Additionally, the design

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must be aimed directly at the level of reliability desired as a procedure for minimizing design redundancy or design insufficiency.

In the development of a pavement design method the U. S. Army Corps of Engineers (CE) adopted the California Bearing Ratio (CBR) tests for defining material strengths and developed the CE design method for road and airfield pavements (1,2). This semi-empirical method was selected in a time of military need for its ease of application by troops in the field. Through the years, the CE design methods for rigid, flexible, and other pavement types have undergone several modifications and are still in use today. These methods are deterministic in that they provide for design of new pavements with respect to a specific failure criterion, and do not provide for analysis of gradual deterioration in the respective modes, or "system drift." This implies sudden failure of pavements upon application of some computed quantity of traffic applications.

Major research programs have been undertaken in the past decade to advance CE design procedures and to improve overall design and management capabilities. In the early 1970's the Waterways Experiment Station (WES) initiated research programs to improve the CE design procedures as well as to improve design procedures of other agencies.

Among these programs was a program of study that was approved and funded in 1974 to develop life-cycle procedures for pavements based upon pavement deterioration and statistical reliability (3,4). This research is aimed at quantification of deterioration of pavements and assessment of reliability. This program of study, which is currently in progress, is partially sponsored by the U. S. Department of Agriculture Forest Service (FS). The FS is participating in the study as a result of their need to assess damage to roads caused by logging operations (4). Data available, along with data that are being collected, are expected to provide for analysis of damage caused by various types of vehicles. This capability will provide the basis for development of a differential cost analysis procedure to aid in assessment of maintenance cost to private sector timber industry.

The Department of Defense, through the CE, is participating in the effort as a result of determination of the need not only to predict deterioration of roads in a military scenario, but due to the need to assess pavement reliability in military, tactical, and logistical operations. This capability is a major step in the direction of overall systems reliability that includes ground and air vehicles as well as the mediums (pavements) upon which they operate.

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The needs of these governmental agencies, based upon financial as well as operational criteria, then have given rise to this research effort to develop procedures for life-cycle management using deterioration and reliability concepts. This paper describes the first phase of this research program.

Objective

The objective of this study was to investigate the hypothesis that effective pavement life-cycle management can be achieved through utilization of deterioration and reliability concepts. This hypothesis was evaluated through a study to develop methodology to predict deterioration and to determine pavement reliability, respectively. In order to accomplish this hypothesis investigation, several intermediate objectives were set forth as follows:

a. Utilize the surface rutting mode of deterioration to develop a pilot deterioration prediction procedure.

b. Further develop the rutting prediction procedure into a stochastic reliability assessment system.

c. Combine the deterioration and reliability models into a deterioration and reliability analysis procedure for use in life-cycle management. This procedure is a pilot procedure that incorporates the rutting mode of deterioration.

c. Provide a base for expanding these developments to include other modes of deterioration.

Accomplishment of these objectives establishes a technological base for the development of an effective life-cycle management procedure.

Scope of work

The scope of work was designed to effectively provide for accomplishment of the objectives. The initial efforts consisted of a search of existing data to determine whether enough rutting data were available to provide a basis for development of the deterioration and reliability models. The data were analyzed and, being found tentatively satisfactory, were utilized for this purpose.

Literature was reviewed and studies were made to determine the most suitable method of analysis of the available data. Upon selection of methodology for data analysis, a major portion of the

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research effort consisted of analysis of data and comparison of existing data to that being accumulated in ongoing field evaluations.

As deterioration and reliability models came forth from the analysis, computer programs were developed to provide for computerized operation of the various models. Ultimately, deterioration and reliability models for the rutting mode were developed for unsurfaced, gravel-surfaced, and two- and three-layer flexible pavements, respectively. These models were then combined to provide for deterioration and reliability analysis as well as for differential damage analysis where mixed traffic occurs. This system is termed the Differential Analysis System (DAS).

PART II: DATA COLLECTION AND CURRENT STUDIES

The CE design method has required revalidation and revision since its adoption due to the ever-changing nature of traffic. Therefore, it has been necessary for the CE to conduct prototype tests over the years to provide data to serve as a basis for revalidation and change. The net result of such an extended series of tests has been the accumulation of myriad prototype pavement performance data. The data are necessarily in terms usable by the early CE design methods, namely rut depths, thickness of layers, strengths of layers and subgrades in terms of CBR, and vehicle characteristics which include number and configuration of wheels, tire pressures, and wheel loads.

The end result of the aforementioned data search was that a large sample of high-quality rutting data was available that applied to two- and three-layer flexible pavements, as well as to gravel-surfaced and unsurfaced facilities. The data were initially termed suitable if the variables were within appropriate ranges and were all included and deliberately recorded. Criteria for rejection of certain data were based on range, reaction of test pavements, and engineering judgment with respect to overall suitability.

The data derived from this data search are used in the development of the constitutive deterioration and reliability models. The availability of such a quantity of data on deterioration in terms of rutting on CE-designed pavements is the basis for the selection of rutting and CE design parameters to conduct this basic research on deterioration and reliability. With additional data, the model may be expanded to other deterioration modes and even to other design procedures according to the needs of other governmental agencies.

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In order to effectively achieve the overall goals of the pavement deterioration program, an inter-agency agreement (3) was entered into by the CE and FS to develop ways to predict deterioration and assess reliability. The agreement not only called for the pilot studies to develop methodology using existing data, but also instituted a large-scale field testing program to accumulate actual deterioration data pertinent to FS and CE roads for use in validation of this procedure for employment by FS and CE agencies. The modes of deterioration considered paramount for this study were rutting, roughness, slipperiness, cracking, and surface loss on aggregate-surfaced roads. Currently, approximately 50 test sites have been selected throughout the United States at various regional locations in areas having suitable design and traffic features to provide a deterioration environment. Test sections have been established at these test sites, and various testing procedures are conducted on the pavement structure to measure deterioration in the different modes.

To determine type and quantity of traffic that brings about deterioration, the traffic is monitored by a combination of electrical counters and visual observation samples. These field tests have been in progress for approximately two years. The combination of tests and traffic monitoring, when successfully pursued over a period of approximately six years, is expected to provide abundant data for deterioration and reliability system validation.

PART III: DEVELOPMENT OF DETERIORATION MODELS

Initial data analysis

The primary objective in the analysis of existing data was the establishment of the rate of rut depth (RD) change as a function of the independent variables. In this instance, where up to eight independent variables were involved, it was recognized early that the method of data analysis would be critical in terms of time, cost, and overall results of the analysis.

Regression analysis procedure

The procedure of analysis ultimately selected for use is an orderly method of developing mathematical relations from sets of data using multiple regression analysis. This procedure was developed by Lu, Lytton, and Moore (5), although the basic methods have probably been employed by others due to its direct approach to the analysis of data. The procedure utilized is termed a two-step constrained regression procedure. The first step of this method is essentially

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a selection regression procedure using a multiplicative model to obtain the approximate exponents of the independent variables. The second step determines the coefficients of linear combinations of the products. The final model is selected based upon four factors:

- a. As simple an expression as can reasonably describe what is actually taking place in terms of the dependent variables and reflecting the effect of the independent variables.
- b. High correlation of the model.
- c. Small prediction error.
- d. Satisfaction of physical constraints.

The variables involved in the regression equations are tabulated as follows:

- a. RD \equiv rut depth in inches.
- b. P \equiv equivalent single-wheel load in pounds.
- c. t_p \equiv tire pressure in pounds per square inch.
- d. R \equiv number of load repetitions.
- e. t_i \equiv layer thickness in inches.
- f. C_i \equiv layer strength in CBR.

The total number of variables changes from one pavement type to another depending upon the number of layers that make up the pavement. The procedure described below is in general terms and applicable to all of the pavement types.

The final step in equation development is determining the rut depth as a function of the other variables. The equations thus derived take the form:

$$RD = f(P, t_p, R, t_i, C_i) + E_1$$

where E_1 is the regression error due to lack of fit of the new equation, stochastic variation of the variables and climatic variations, and other factors not explained in the variables.

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Development of regression models

The existing data were used to develop models for rutting in the manner described in the preceding paragraphs. Experience and familiarity in the area of CE pavement design procedures provided some insight into the probable behavior of the variables, and therefore some transformations were attempted in the case of many of the variables. The thickness equations currently in use by the CE (6) were studied to determine the most likely form that some of the variables might assume.

The final forms of the rutting models resulting from the regression analysis of the four categories are listed below. Included with each model are the standard error (SE) and the coefficient of correlation r .

a. Unsurfaced facility model:

$$RD = 0.110 \left[\frac{P^{0.4925} t_p^{0.8548} R^{0.5018} (\log t)^{0.4293}}{C_1^{1.9773} C_2^{1.2015}} \right]$$

where SE = 0.399, $r = 0.9403$

b. Gravel-surfaced facility model:

$$RD = 0.1741 \frac{P_K^{0.4707} t_p^{0.5695} R^{0.2476}}{(\log t)^{2.0020} C_1^{0.9335} C_2^{0.2848}}$$

where SE = 0.294, $r = 0.9117$

c. Two-layer flexible pavement model:

$$RD = 1.9431 \left[\frac{P_K^{1.3127} t_p^{0.0499} R^{0.3240}}{[\log (1.25 t_1 + t_2)]^{3.4204} C_1^{1.6877} C_3^{0.1156}} \right]$$

where SE = 0.411, $r = 0.8779$

d. Three-layer flexible pavement model:

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$$RD = 0.03117 \frac{P_K^{1.5255} t_p^{0.0897} R^{0.3450} C_1^{0.7617} C_2^{-0.5505} C_3^{-0.3089}}{[\log(1.25 t_1 + t_2)]^{0.8847} (\log t_3)^{1.1674}}$$

where SE = 0.444, r = 0.8418

The variables influencing the rut depth for the unpaved categories are listed in Table 1, while the variables in the flexible pavement models are listed in Table 2.

TABLE 1.--VARIABLES FOR UNSURFACED AND GRAVEL-SURFACED FACILITY RUTTING MODELS

Index	Variable
1	RD = rut depth (in.)
2	P = equivalent single-wheel load (ESWL) (lb)
2a	P _K = equivalent single-wheel load (ESWL) (kip)
3	t _p = tire pressure (psi)
4	t = thickness of top layer (in.)
5	*C ₁ = CBR of top layer
6	*C ₂ = CBR of bottom layer
7	R = repetitions of load or passes

* C₁ < C₂ for unsurfaced facilities

C₁ > C₂ for gravel-surfaced facilities

PART IV: DEVELOPMENT OF RELIABILITY MODELS

Development procedure

The deterioration models for rut depth analyses of the four respective pavement types as developed previously are necessarily deterministic models. They represent not necessarily the best fit of all the data, but instead a "good fit" as indicated by the error and correlation values. To further expand the applicability and utility of the models, statistical reliability concepts are invoked to

TABLE 2.--VARIABLES FOR THREE-LAYER FLEXIBLE
PAVEMENT MODEL

Index	Variable
1	RD = rut depth (in.)
2	P = equivalent single-wheel load (ESWL) (lb)
2a	P_K = equivalent single-wheel load (ESWL) (kip)
3	t_p = tire pressure (psi)
4	t_1 = thickness of asphalt pavement (in.)
5	t_2 = thickness of base (in.)
6	C_1 = CBR on top of base
7	t_3 = thickness of subbase (in.)
8	C_2 = CBR on top of subbase
9	C_3 = CBR on top of subgrade
10	R = repetitions of load or passes

account for the variability of all input data and to predict rutting in terms of expected rut depth and variance from that expected rut depth. This concept provides for models for each pavement type that utilizes a total description of the input variables in terms of means and variances of a set of values for each variable. This provides for an accounting of the variability of pavement properties in a statistical manner instead of accepting only changes of values of measured parameters. The statistical determination of the rut depth in terms of expected value and variance provides not only for better analysis of rut depth in terms of an expected rut depth and a probable deviation from that value, but also for accounting for material variability in a statistical manner. The primary benefit of using total input data and determining the expected values and variances of a probability density function on rut depth is the ability to evaluate the reliability of the pavement. The reliability of a facility can be determined in terms of the probability that a given rut depth will occur under given circumstances. It follows then that such a system can be an excellent evaluation tool as well as a design tool. The great advantage as a design procedure is the capability to adjust reliability or conservatism to a desired value and selection of the design parameters to suit those conditions. In order to address

these concepts of reliability and the accounting for material variability, it was necessary to develop stochastic models for the definition of a probability density function of the rut depth.

If rut depth (RD) is considered a continuous, random variable with some probability density function, $f(RD)$, the expected value of $H(RD)$ is defined as

$$E[H(RD)] = \int_{-\infty}^{\infty} H(RD) f(RD) dRD$$

The expected value of RD is the mean or average of RD, which is termed μ_{RD} , or $\mu_{RD} = E(RD)$. The variance of RD as a variable is denoted by σ_{RD}^2 and is defined to be:

$$\sigma_{RD}^2 = E[(RD - \mu_{RD})^2]$$

Occasionally, taking the expected value of a complicated function can be a difficult process as in the case of the rut depth models previously shown. In order to overcome these difficulties, the expected value was approximated by taking a Taylor's series expansion and truncating all but the first three terms:

$$f(RD) = f(RD - \Delta RD) + f'(RD - \Delta RD)\Delta RD + 1/2 f''(RD - \Delta RD)\Delta RD^2 + \dots$$

If ΔRD becomes $RD - \mu_{RD}$, then the final generalized form can be expressed as follows:

$$E[f(RD)] = f(\mu_{RD}) + 1/2 f''(\mu_{RD})\sigma_{RD}^2$$

Taking the variance of the rut depth models was also a painstaking operation, further complicated by the forms imposed upon some of the variables. The Taylor's series expansion was again applied. The variance of the rut depth models is denoted by $V(RD)$ and is expressed as:

$$V(RD) = [f'(\mu_{RD})]^2 \sigma_{RD}^2 + 1/4 [f''(\mu_{RD})]^2 \sigma_{RD}^4 + \sigma_{lof}^2$$

in which σ_{lof}^2 is the variance of lack of fit.

The expected value and variance models of each of the four pavement types have been developed using the first three terms of a Taylor's series expansion and have been programmed for computer solution as part of the analysis model.

Determination of reliability

As has been previously stated, reliability as defined and used in this study is the probability that the rut depth will not exceed some predetermined value subject to conditions that are expressed by the independent variables. If a normal distribution on the dependent variable is assumed, the probability that the rut depth will not exceed some maximum value RD_A can be calculated using the equation

$$P = \frac{RD_A - E(RD)}{\sqrt{V(RD)}}$$

where $E(RD)$ is the expected value of the rut depth as determined from the appropriate model and $V(RD)$ is the variance of the rut depth as similarly determined. The value P represents the variable Z of the cumulative distribution function $F(Z)$. In order to determine reliability R , or that is, the area under the distribution curve defined by $E(RD)$ and $V(RD)$ and to the left of the maximum rut depth (RD_A), enter a normal distribution function table from a statistics handbook with a value of P (or Z) determined previously and determine the area under the distribution ($F(Z)$), which is the reliability R . As an illustrative example, assume the following values:

$$RD_A = 3 \text{ in.}$$

$$E(RD) = 2 \text{ in.}$$

$$V(RD) = 1 \text{ in.}$$

$$\text{then } P = \frac{RD_A - E(RD)}{\sqrt{V(RD)}} = \frac{3 - 2}{\sqrt{1}} = \frac{1}{1} = 1 . \text{ Entering a normal distribu-}$$

tion table with a value of $Z = 1$, it can be seen that $R = F(Z) = 0.8413$. Or, it can be said in this case that there is a probability of 0.8413 that the rut depth will not exceed a predetermined maximum value of 3 in.

PART V: DIFFERENTIAL ANALYSIS SYSTEM

The rutting models previously described have been entered on a computer program to form the base of the Differential Analysis System (DAS), which provides for a utilization of the rutting models to determine the rate of deterioration and/or reliability of any of

the four types of facilities described in terms of rutting. The term "differential" has been given to the computational system to emphasize the fact that differences in results caused by changes in input can be determined by the user in any assessment of damage caused by various vehicle types or the effects of changes in the structure. The DAS provides for one automatic iteration of the computational processes. Differential analysis as described above can be achieved simply by repeated iterations of the system while changing any variable or variables desired. The system as shown is adequate for limited use where the various models apply and is adequate to develop the original hypothesis that life-cycle management can be achieved through deterioration and reliability concepts.

The second stage of the DAS will provide for optimization of rutting and reliability values with respect to constraints imposed through the input of values or ranges of values representing the variables. Additional optimization will be achievable in terms of design and rehabilitation costs as well as selection among the four pavement options. As data pertinent to other pavement types, especially rigid pavements and selected hybrid pavements, become available, models will be included for their analysis.

Range and distribution of variables

The DAS is considered to be applicable to design and evaluation problems where normally encountered values of the variables are utilized. The range of applicability of any computational system is constrained by, if not limited to, the boundary conditions of data upon which it is based.

Utilization of the DAS

There are numerous applications of the DAS that can be made by those concerned with life-cycle management or any aspect thereof. As is the case with any similar system, validation is required to render the DAS directly applicable to specific locales having unique conditions. This version is, of course, in terms of rut depth as the dependent variable and major item of analysis. Validation of the DAS not only can achieve local applicability, but can incorporate the other deterioration modes as a data base is made available. Field data collection, for validation purposes, that is currently under way has been described previously.

Although the specific applications of the DAS are numerous and necessarily depend upon user needs, some of the more pertinent applications are described as follows:

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a. Design and evaluation: The DAS is directly applicable to CE design and evaluation problems in the same sense as are current criteria due to similarity in data bases and results. The added features of the DAS are namely the ability to (1) modify limiting failure criteria (rut depth), (2) adjust conservatism to any desired degree by imposing a required degree of reliability, and (3) determine the reliability of a facility.

b. Optimization: Iterations of the DAS while making changes in appropriate variables can provide for optimization of a design with respect to cost, reliability, serviceability, layer properties, and materials.

c. Differential analysis: Iterations of the DAS provide directly for the analysis of the effects of different quantities and magnitudes of loads. The equivalent single-wheel concept (6) makes this possible by providing the capability to incorporate various vehicle configurations. This feature provides a quantitative basis for assessment of damages caused by various categories of vehicles and, when used on a relative basis would not require locality validation of the DAS.

d. Planning: The DAS can be considered an effective stochastic-type planning tool for quantitative estimation of future maintenance and repair needs as well as time-to-maintenance estimation. This feature, in connection with such procedures as CPM and PERT, can be used to effectively program work loads and expenditures.

e. Military operations: The tactical and logistical operations that could benefit from use of the DAS are too numerous to mention in detail. Such considerations as optimization of construction capabilities by constructing facilities having only a required reliability, and using facility reliability concepts to aid in tactical planning and maneuvers are key considerations that could be better quantified using DAS concepts.

The use of the DAS as it exists herein necessarily includes use of the CBR method of strength evaluation, which is in itself not a true physical material parameter. This feature is not to be considered a deterrent, however, to prospective users bound to other design procedures. Material strength parameters can be stated in any suitable terms where a sufficient data base exists for validation. True material parameters, such as Poisson's ratio (μ) and elastic properties (E), in various forms can be utilized and would provide for a more rational approach to the overall operation. Other methods

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of portraying strength can be used where data are available. In all cases, any bias is removed in the actual correlation indicated during the validation stage and should be the basis of judgment as to whether a particular procedure is employed.

PART VI: CONCLUSIONS

The conclusions drawn as a result of this study are as follows:

- a. The hypothesis that effective pavement life-cycle management can be achieved through the use of deterioration and reliability concepts has been investigated and proven.
- b. Models were developed that effectively portray the deterioration of a facility and assess its reliability in terms of the rutting mode of deterioration.
- c. The deterioration and reliability models show high correlation and small residual error and, therefore, when combined to form the heart of the DAS, should provide for effective rut depth prediction and reliability assessment.
- d. The DAS can be used for the purposes indicated in the section entitled "Utilization of the DAS."
- e. The DAS, as a first-generation system, provides a technological basis for development of a complete life-cycle management system for all modes of deterioration pertinent to all pavement types through expansion and validation as data are made available.
- f. The DAS can be used in its present form for differential analysis on roads where damage incurred by various vehicle types must be determined as a basis for cost assessment.

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