Existing Methods for the Structural Design of Aggregate Road Surfaces on Forest Roads

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The Forest Service currently uses several aggregate surfacing design methods. Current design methods range from the "best-estimate" method to techniques that were developed or adapted by the different forests or regions. These techniques have various deficiencies; the best-estimate method has been criticized by the General Accounting Office. Also, several of these methods do not provide the technical capability to analyze unusual design situations, the effects of changes in the use of Forest Service roads, or the ability to incorporate technological advances. Such problems as different levels of failure criteria, seasonal haul traffic, variable tire pressures, and others have also not been met by the USDA Forest Service *Interim Guide for Thickness Design of Flexible Pavement Structures*. To meet these needs, the Forest Service recommended that a project be initiated to develop a second surfacing guide and computer program for the structural design of aggregate-surfaced and earth roads, utilizing existing technology as much as possible. This paper focuses on a description and evaluation of nine design methods that were deemed most suitable for use in Forest Service projects. The design methods evaluated include all of the known methods currently being used within the Forest Service. The other major organization performing aggregate-surfaced or earth design, the Corps of Engineers, is also represented. Recommendations are made pertaining to the need for field studies to refine the design algorithms for aggregate-surfaced and earth roads.

Because of shortcomings in the current design methods for aggregate-surfaced roads (*1*), the U.S. Forest Service (USFS) in 1988 reviewed the current direction regarding the design of such road surfacings and produced a surfacing design evaluation report for internal use and discussion (*2*). One of the key recommendations resulting from that report was to develop a surfacing design guide for aggregate-surfaced and earth roads using existing technology.

A project was therefore initiated to develop a guide and companion computer program to assist in the structural design of aggregate-surfaced and earth roads. A Forest Service Technical Advisory Board consisting of representatives from several Forest Service regions was appointed to provide technical guidance during the project. The initial tasks of the project focused on the review of existing technology related to the structural design of aggregate-surfaced roads. The results of that review and evaluation are described and the information contained in the resulting report (*3*) is summarized. This paper is intended as a guide to the different design methods and their interrelationships. One of the objectives is to communicate to others the nature of the research in the structural design of aggregate-surfaced roads. A similar report was subsequently published by the Corps of Engineers (*4*) in 1989 after the completion of this review.

Several existing relationships were identified as potential candidates for this design guide; however, no clear choice for adoption was discovered and all design methods currently available had some serious limitations. In fact, there was considerable disappointment with the current state of existing technology. However, after considerable review, a relationship developed by the Corps of Engineers in 1978 was selected as the thickness design algorithm for inclusion in the design guide and computer program. This algorithm has been used little, if at all, in the fields; however, this is also true for most of the design algorithms reviewed. The equation was developed by researchers at the Corps' Waterways Experiment Station (WES) using previous field data. The intent during its development was to provide a relationship as a starting point that could then be refined through field experiments.

The authors would like to emphasize that the need for field studies to refine the design algorithm is still a critical item in the development of aggregate-surfacing design techniques for use by the Forest Service. Focused, small-scale field validation experiments are vital to the continued use and acceptance of any design method selected.

Nine design methods that were deemed to be most suitable for use in Forest Service projects are described. The design methods include all of the known methods currently being used within the Forest Service. The other major organization performing design of aggregate-surfaced or earth roads, the Corps of Engineers, is also represented. An evaluation of the design methods and recommendations for the selected design procedure are included. Other recommendations include the desirability of field studies for refinement of the design algorithms for aggregate-surfaced and earth roads. One such field study is the Central Tire Inflation Project at the Waterways Experiment Station in Vicksburg, Mississippi, which is a cooperative effort between the USFS, the Corps of Engineers, and FHWA.

DESCRIPTION OF DESIGN METHODS

Nine major design methods are summarized and evaluated:

1. U.S. Army Corps of Engineers Method;
2. USFS Region 4 implementation of Corps rutting equation;

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3. USFS Surfacing Design and Management System (SDMS);
4. USFS Region 8 Analysis Road Materials System (ARMS);
5. AASHTO low-volume road design method (1986);
6. USFS Chapter 50 design method;
7. USFS Region 1 seasonal surfacing method;
8. Willamette National Forest "Seasurf" design method; and
9. FHWA report.

The design methods identified above can be categorized into three logical groups. Group 1 (items 1 and 2 above) includes work performed by the U.S. Army Corps of Engineers and the USFS Region 4 implementation of one of the Corps' rutting equations. In addition, a draft version of their aggregate-surfacing design guide for roads and airfields was reviewed. The three basic reports identified in this draft report are by the Corps of Engineers (*5–7*). Remboldt of Region 4 has adapted the design equations from Technical Report S-78-8 (*5*) for use in design (Remboldt, unpublished data).

Group 2 (items 3, 4, and 5 above) may be termed the SDMS group. This includes the SDMS manual and computer methods, the Region 8 ARMS Program, and the 1986 AASHTO low-volume road design method (*8*). The ARMS program is essentially a computerization of the SDMS manual equations, while the AASHTO low-volume road design method provides nomograph solutions to the SDMS manual equations.

Group 3 (items 6, 7, and 8 above) includes three closely related methods—the USFS "Chapter 50" design method, the USFS Region 1 seasonal surfacing method, and the Willamette National Forest "Seasurf" design method. The seasonal surfacing method uses a modified Chapter 50 design to include seasonal characteristics of materials. The Willamette "Seasurf" design method is similar to the USFS Region 1 seasonal surfacing method.

The final design procedure reviewed (item 9) is a report for FHWA (*9*), which contains elements from each of the above three groups and incorporates three levels of design. Level C is the simplest design method and consists of the equation developed by Hammitt (*6*) (Group 1). Level B is a more complex level and consists of the AASHTO design procedure from the 1972 Interim Guide (*10*) for a one-layer system (Group 2). Level A is the most complex level and consists of the manual design procedure from SDMS (Group 3).

The remainder of this section provides an overall perspective of the foregoing design methods. All the design methods for aggregate-surfaced and earth roads found in the literature are generally related to each other and typically can be traced back to two basic studies: (a) the California bearing ratio (CBR) design method itself, developed by the California Division of Highways (*11*) for flexible pavements and adapted to airfield pavement design by the Corps of Engineers, and (b) the AASHO Road Test (*12*). The lineage of all subsequent aggregate-surface design methods can be traced to one or both of these studies.

Figures 1 and 2 are representative schematics of the genealogy, as it were, of these design procedures from the Corps' work and the AASHO Road Test. Figure 1 shows the roots of the CBR design method with the California Division of Highways. This method was derived from empirical studies of flexible pavement performance in the 1920s and 1930s. During World War II, the Corps of Engineers was faced with the task of designing airfield pavements for the war effort. They selected California's CBR design method as a starting point and undertook an extensive series of field studies to adapt it for airfields (*13*). The work to refine design methods for low-volume aggregate-surfaced and earth facilities has continued with the work by Hammitt (*6*). Barber et al. (*5*), and the new Corps aggregate surfacing design manual (*7*).

As shown in Figure 1, the Forest Service derived its modified *f*-factor from Hammitt's work for use in Chapter 50. This was combined with AASHTO's 1972 Interim Guide to produce the 1974 version of the Chapter 50 design method. The Forest Service Region 1 and Willamette seasonal design methods are direct descendents of the Chapter 50 design method.

Two of the three levels of design presented in the FHWA report (*9*) are also shown in Figure 1. The Level C design uses Hammitt's equation, whereas the Level B design uses the 1972 AASHTO Interim Guide design procedure for a one-layer system.

The work by Barber et al. (*5*) was a continuation of the Corps' investigations into low-volume aggregate-surfaced and earth road design. As shown in Figure 2, this research led to both the development of the manual equations in the Forest Service SDMS and the algorithms used in the computer model. Remboldt from Forest Service Region 4 also used the rutting equation to derive his design method. Both the ARMS procedure (from Region 8) and the AASHTO low-volume road design method were derived from the SDMS manual equations. Some modifications were made in ARMS, but the AASHTO guide adopted the equation with no modifications. Finally, in the report by Alkire for FHWA (*9*), these equations were used as the basis for his Level A design. Each of these design methods is described in more detail below.

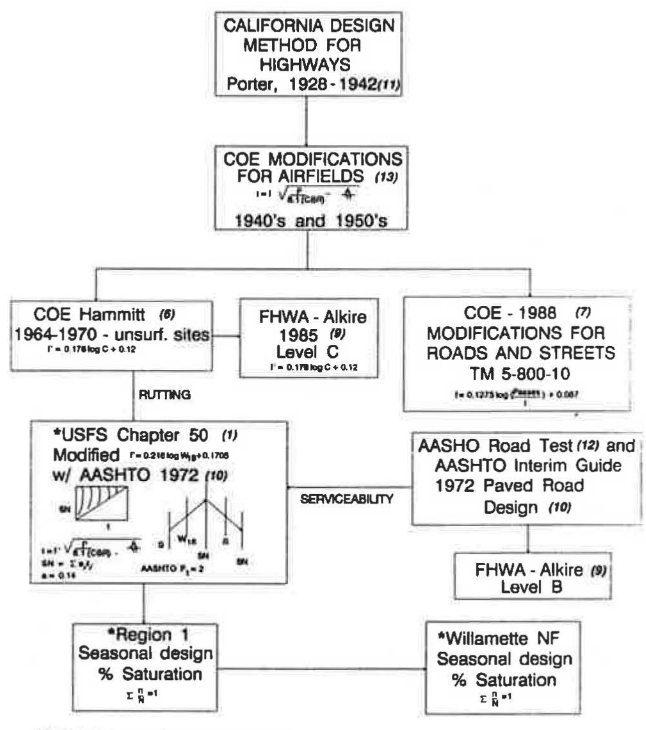

FIGURE 1 Design method relationships originating from California for aggregate-surfaced and earth roads.

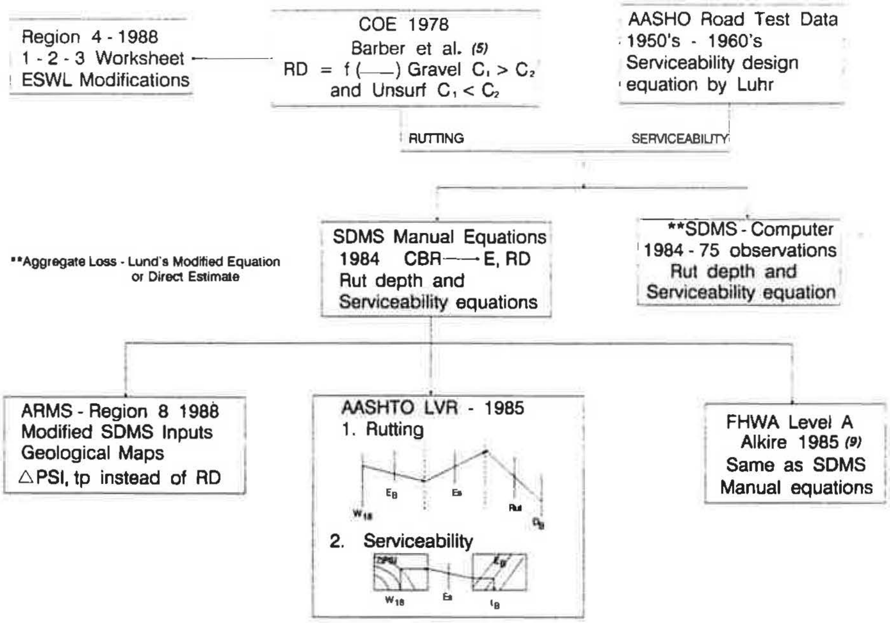

FIGURE 2 Design method relationships originating from the Corps of Engineers for aggregate-surfaced and earth roads.

U.S. Army Corps of Engineers Method

This aggregate thickness design procedure is based on the Corps' early work on flexible pavements. In the 1950s, WES developed a set of design curves for flexible pavements based on the CBR (*14*). Mathematically, the form of the equation is

$$t = f\left[\frac{P}{8.1\ (\text{CBR})} - \frac{A}{\pi}\right]^{0.5} \tag{1}$$

where

t = design thickness (in.),
f = percent of pavement design thickness,
= 0.23 log C + 0.15 (where C = coverages),
P = single or equivalent single-wheel load (lb),
A = tire contact area (in.^{2}) = (load/tire contact pressure), and
CBR = California bearing ratio of underlying material.

The design thickness (t) is the thickness of the asphalt concrete and base course that would be required to protect the subgrade having a certain strength (CBR) for a number of coverages (C) of a given load (P).

In the late 1960s, WES built test sites to develop a similar equation for determining thicknesses for unsurfaced airfields, and this is documented in Hammitt's report (*6*). The test sites contained clay materials of controlled strengths (CBR) and different depths. The failure criteria used were based on permanent deformation or rutting and elastic deformation.

The number of coverages required to cause failure was recorded. Equation 1 can be solved for f since t, P, CBR, and A are all known. Because the test sites were unsurfaced, f is referred to as f', or the ratio of the unsurfaced thickness to the flexible pavement thickness:

$$f' = t\left[\frac{P}{8.1\ (\text{CBR})} - \frac{A}{\pi}\right]^{-0.5} \tag{2}$$

It was then possible to plot f' against the failure coverage and, through linear regression analysis, obtain the following relationship:

$$f' = 0.176 \log C + 0.12 \tag{3}$$

where the terms are as previously defined. Substituting f' for f in the original thickness equation (1) results in the following:

$$t = (0.176 \log C + 0.12)\left[\frac{P}{8.1\ (\text{CBR})} - \frac{A}{\pi}\right]^{0.5} \tag{4}$$

This expression then determines the thickness of the cover material for unsurfaced roads required to prevent subgrade failure. The strength of the cover material is then determined (*14*). The tire pressure, wheel load, and number of coverages are required to determine the CBR of the cover material.

In 1978 another study was published at WES by Barber et al. (*5*), which led to additional design equations for aggregate-surfaced roads. Existing rutting data from previous work at WES for earth, gravel-surfaced, and flexible pavements were utilized to develop deterioration and reliability models. Once the models had been developed, computer programs were written. The models all predicted rut depth of the surface layer given the load, tire pressure, surface layer thickness, and strengths of the material layers in CBR. This study also recommended field studies to validate the relationships developed; however, conversations with Barber in 1988 indicated that the field studies were not performed.

The model developed for aggregate-surfaced roads is shown below and assumes that the top layer is stronger than the bottom layer ($C_1 > C_2$):

$$RD = 0.1741\left[\frac{P_k^{0.4704} t_p^{0.5695} R^{0.2476}}{(\log t)^{2.002} C_1^{0.9335} C_2^{0.2848}}\right] \qquad (5)$$

where

RD = rut depth (in.),
P_k = equivalent single-wheel load (ESWL) (kips),
t_p = tire pressure (psi),
t = thickness of top layer (in.),
R = repetitions of load or passes,
C_1 = CBR of top layer, and
C_2 = CBR of bottom layer.

In 1988, the Corps aggregate-surfacing design procedure (7) was brought in line with the existing Corps flexible pavement procedure in the interests of consistency. Figure 3 is from the 1988 draft version of Technical Manual 5-822-30 (7). The design equation is

$$t = \left[0.1275 \log\left(\frac{\text{Passes}}{I}\right) + 0.897\right] \times \left[\frac{\text{ESWL}}{8.1\ (\text{CBR})} - \frac{A}{\pi}\right]^{0.5} \qquad (6)$$

where

Passes = no. of repetitions of 18-kip single-axle loads;
I = traffic index, a value of 2.64 is used for 18-kip dual wheel single-axle loads;
ESWL = equivalent single wheel load (lb);
CBR = California bearing ratio of underlying material; and
A = contact area of one tire (in.^{2}).

This equation is similar to Equation 1, with the exception that the *f*-factor has been modified. In conversations with Donald Ladd at WES in 1989, it was determined that the *f*-factor was developed from test data that had not been published. Tests had been performed on aggregate-surfaced roads, but funds for that project were subsequently cancelled, hence the lack

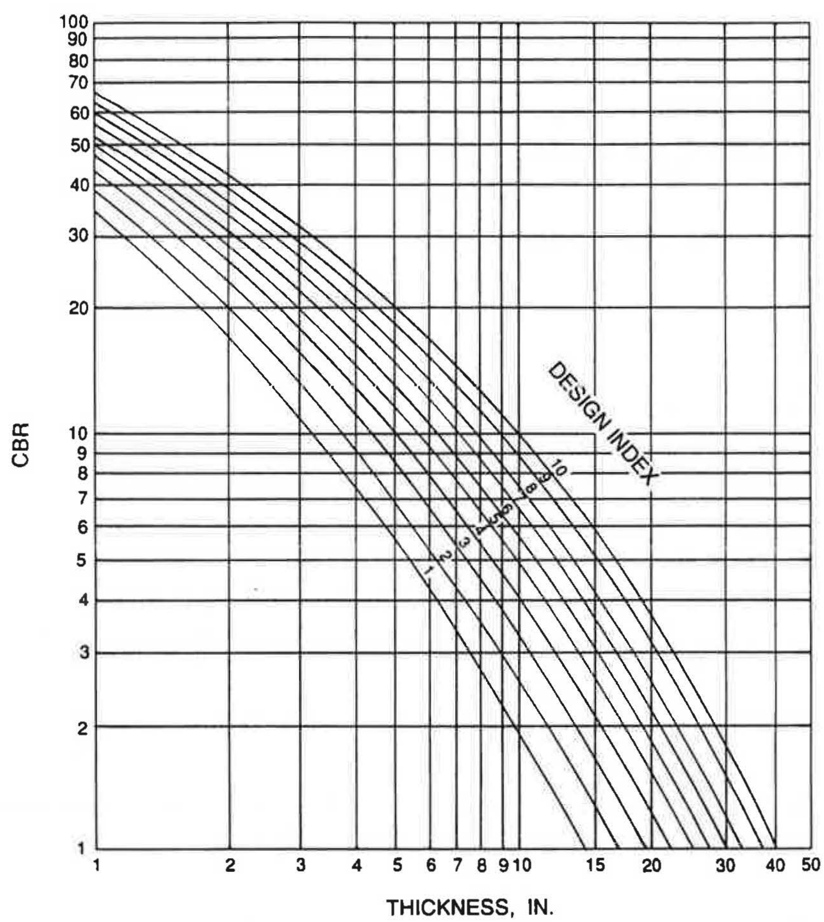

FIGURE 3 Design curves for gravel-surfaced roads (*7*).

of published information. At this time, the failure criteria associated with this design equation are unknown.

USFS Region 4 and Corps Rutting Equation

Rutting was selected as the failure criterion for aggregate road design in Region 4 (Remboldt, unpublished data). The design equation used in this procedure comes from work by Barber et al. (*5*) described previously (Equation 5). To obtain the ESWL, Region 4 has derived a regression model for use as follows:

$$\text{ESWL} = C1 * \text{Lg} + C2 * \text{Lg} * \text{Da} \qquad (7)$$

where

$C1$ = 0.3209 (single axles) or 0.1646 (tandem axles),
$C2$ = 0.0151 (single axles) or 0.0127 (tandem axles),
Lg = group load (kips), and
Da = depth of aggregate (in.).

This equation is not based on the AASHO Road Test data nor that of Chapter 50. It is a new relationship based on regression equations that relate ESWL with actual load configurations. Remboldt indicates that the calculations used elastic-layered equations developed by Ahlvin and Ulery (*15*).

USFS Surfacing Design and Management System

The SDMS project evolved over a period of 15 years (1972–1987) and was known by several names, including Pavement Design and Management System (PDMS), Low Volume Roads (LVR), and SDMS. In 1972 the Forest Service and the University of Texas initiated a cooperative study to develop a pavement management system for the Forest Service road

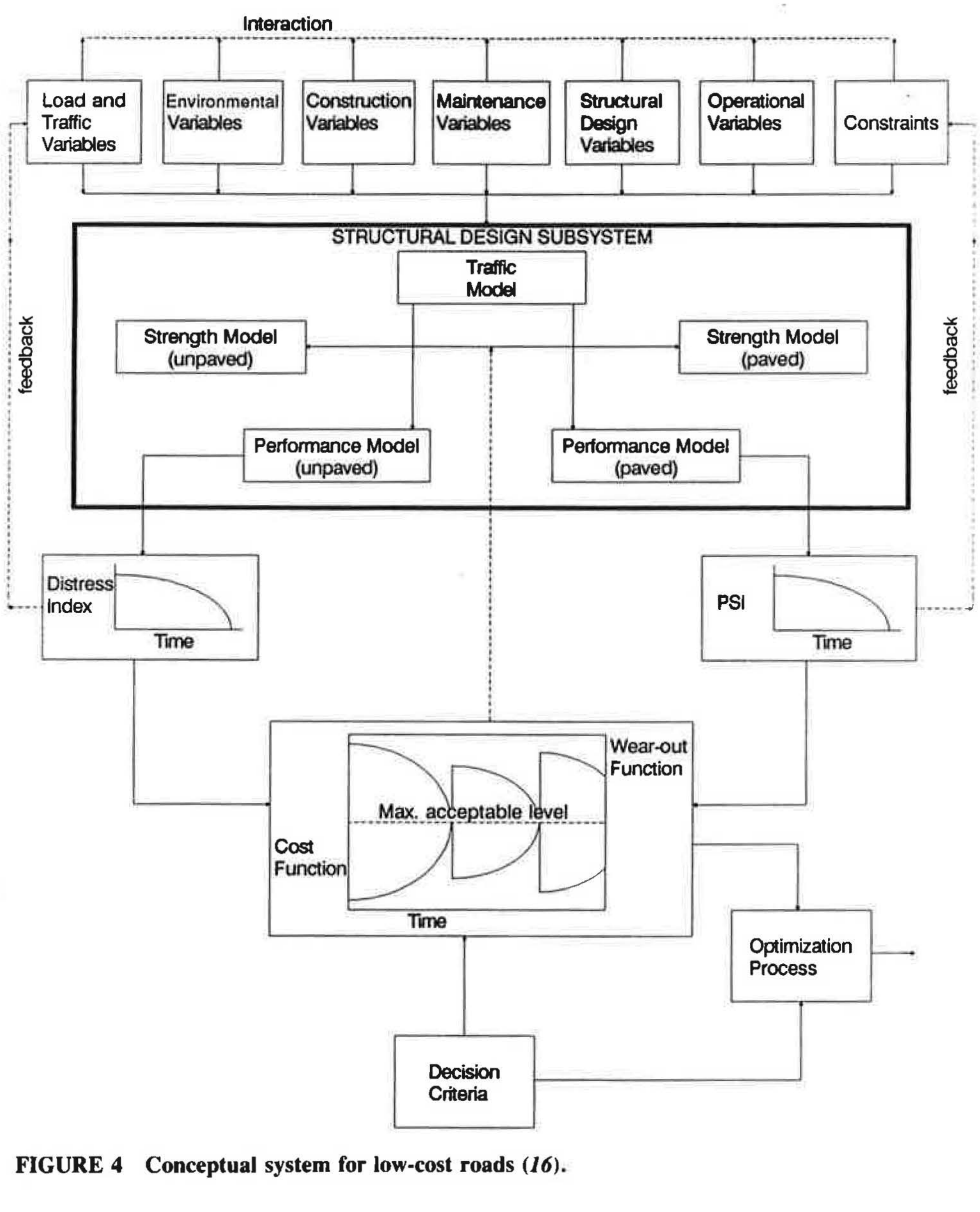

FIGURE 4 Conceptual system for low-cost roads (*16*).

TABLE 1 CLASSIFICATION OF INPUT VARIABLES FOR LVR

CATEGORY OF INPUT VARIABLES	SPECIFIC INPUT VARIABLES
MISCELLANEOUS INPUT	Problem Identification Output Formats Total Number of Materials Available Length of Analysis Period Width of Each Lane Number of Cards with Time Dependent Variables Interest Rate Road Type (Asphalt Concrete, Aggregate, Bituminous Surface Treatment) Number of Performance Periods Flag for Calculation of User Delay Cost
PERFORMANCE VARIABLES	Regional Factor Initial Serviceability Index Terminal Serviceability Index Serviceability Following Rehabilitation Non-Traffic Terminal Serviceability Rate of Non-Traffic Serviceability Reduction Variables for Aggregate Loss Equation
TIME DEPENDENT VARIABLES	Traffic (Load and Frequency) Maintenance Costs Aggregate Loss
PERFORMANCE PERIOD VARIABLES	Length of Performance Periods where Performance Period is Defined as Time Between: 1) Initial Construction and First Rehabilitation. 2) Two Major Rehabilitations. 3) Initial Construction and Subsequent Construction Changing the Surface Type.
CONSTRAINT VARIABLES	Maximum Construction Cost Maximum Total Thickness Minimum Thickness of Individual Rehabilitation Maximum Thickness of All Rehabilitations Maximum Thickness of Individual Rehabilitation Minimum Thickness of Top Layer Aggregate Loss from Erosion (Added to Other Aggregate Loss)
REHABILITATION PARAMETERS FOR CALCULATING USER DELAY COSTS	Distance Over which Traffic is Slowed Percent of ADT Through Rehab Zone each Hour Percent Vehicles Stopped Average Delay Average Speed Approaching and Passing Through Rehab Area Model to Use in Calculating User Delay Costs
GRADING AND SEAL COAT VARIABLES	Grader or Seal Coat Passes Speed of Grader and Trucks Distance Cars Follow Grader Cost of Grading or Seal Coat Time Between Gradings and Seal Coats
VEHICLE OPERATION COSTS	Average Operating Costs ($/mi) for Log Trucks and Other than Log Trucks
MATERIAL VARIABLES	Material Description Cost (in place) per cy. Layer Coefficient Minimum and Maximum Layer Thickness Salvage Value Soil Support (for Subgrade)

network. The work was conducted in three phases and three reports were produced:

- Phase I: conceptual study (*16*),
- Phase II: working model (*17*), and
- Phase III: implementation (*18*).

PDMS

In Phase I, the feasibility of developing such a pavement management system was analyzed. This led to the development of a working computer-based model during Phase II. The working model was known as PDMS. In Phase III, the experiences derived from a trial implementation in several offices of the Forest Service were presented.

As a result of this third phase, two additional projects were conducted at the University of Texas. The first of these dealt with the revision of the actual design procedure used in the Forest Service and the integration of PDMS in the U.S. Forest Service road design handbook (*18,19*). The second project was also a three-phase study to develop a data base pertaining to the design and performance of aggregate-surfaced roads. Phase I of this second project analyzed the feasibility of a data base for PDMS (*20*), and Phase II was a pilot study (*21*) designed to field test alternative types of equipment for measuring the variables involved, recommend optimum test section length and measurement frequencies and hardware and software requirements for computerization of the data base, and develop cost estimates for several scenarios to develop the data base. In Phase III, field data were collected during 1984 and 1985 and regression analyses performed (*22*).

LVR

The development and implementation phases of LVR are documented elsewhere (*17,18*). The intent of the LVR program was to computerize the existing Forest Service design procedures (Chapter 50) (*1*) within the conceptual model presented in the Phase I report (*16*). This conceptual model is shown in Figure 4.

The structural design subsystem was the existing Chapter 50 design. The LVR program was written to computerize this design method. The program would generate pavement structures that would meet the performance limitations and constraints provided. As design structures that met these criteria were identified, they were saved and listed in order of increasing total cost. The input variables for LVR are shown in Table 1.

SDMS

The work to develop SDMS took place over a 5-year period (1978–1983) and has been documented best by Luhr (*23*). By 1978 LVR was operating successfully. However, in July 1978, the Forest Service and the University of Texas entered into a cooperative agreement to revise and improve Chapter 50 of the Forest Service Transportation Engineering Handbook. The objective was to improve the flexible pavement design guide by making needed revisions and provide additional capabilities by accomplishing the tasks shown in the text box.

These modifications initially resulted in PDMS. However, during the performance of these tasks, it became apparent that Chapter 50 was inadequate to meet the objectives shown in the text box. Therefore, a new structural design algorithm was required. Subsequently, Luhr (*23*) reviewed the literature and concluded that no existing design procedure was available that addressed the desired capabilities. A decision was then made to develop a new procedure using a combination of theoretical and empirical methods to specifically address the needs of the Forest Service. This new design method became known as SDMS.

In the initial development of the SDMS equations, Luhr (*23*) used an elastic-layered program known as ELSYM5 to analyze the AASHTO Road Test information and concluded

Tasks to be accomplished during SDMS project (1978-1982).

(1) Develop reliability factors for different classifications of roads. Provide the designer with flexibility in accordance with road's present and future classifications. Provide the means for a designer to select appropriate failure criteria for each specific project.

(2) Improve the Rutting Model using a more rational approach. Improve the Aggregate Loss Model in accordance with recent research experience.

(3) Analyze the wheel load equivalencies for single and dual wheels for legally loaded and oversized loads as they presently appear in Chapter 50. Analyze recent information on structural layer equivalencies. Revise the wheel load equivalencies and the structural layer equivalencies in Chapter 50 in accordance with these analyses.

(4) Develop a procedure in Chapter 50 for determining the regional factor.

(5) Provide improved procedures for evaluating the amount, type, frequency, and distribution of traffic over the design life of the roadway surface.

(6) Provide a capability to consider the effects or non-effects of roadway drainage.

(7) Provide a deflection design alternate in Chapter 50.

(8) Analyze the findings from recent pavement and other appropriate research for low-volume roads. Incorporate those significant findings that area compatible with the basic approaches followed in Chapter 50. Such items as vehicle operating cost models and selected findings from the Brazil study associated with the University of Texas should be carefully scrutinized to determine their applicability and potential for enhancement of Chapter 50.

(9) Provide a comprehensive, interactive connection between Chapter 50 and the LVR computer program. Incorporate in Chapter 50 an up-to-date LVR users manual with all appropriate discussion, instruction, figures, tables, and examples of input and output data. In addition, make the appropriate connections and referrals in the LVR users manual with the revised Chapter 50.

(10) Check all figures, tables, nomograph charts, and other supporting material in Chapter 50 for correctness, accuracy, and ease of use. Make changes as needed. Completely rewrite Chapter 50, with an appropriate explanatory text to reflect all of the aforementioned changes, additions, and improvements.

that vertical compressive strain at the top of the subgrade was found to be the most promising parameter to correlate with the Pavement Serviceability Index (PSI). The following equation (eventually used as one of the "manual" equations for SDMS) was obtained from linear regression techniques:

$$\log W_{tx} = 2.15122 - 597.622(\varepsilon_{SG}) - 1.32967 (\log \varepsilon_{SG}) + \log\left(\frac{4.2 - P_t}{4.2 - 1.5}\right) \quad (8)$$

where

W_{tx} = number of applications of axle load x,
ε_{SG} = vertical compressive strain at top of subgrade, and
P_t = terminal value of PSI (terminal serviceability).

For aggregate-surfaced roads, performance models for rutting and aggregate loss were also introduced. The rutting model was obtained using Corps of Engineers data (*5*). Luhr indicates that the equation for the manual design was developed using all the data points from the Corps 1978 report. He also indicates a certain lack of confidence in the published Corps regression equations. The rutting equation is

$$W_{18R} = 0.1044 * RUT^{2.575} * \log_{10} THICK^{5.155} * \left(\frac{E_1}{1{,}800}\right)^{3.434} * \left(\frac{E_2}{1{,}800}\right)^{1.048} \quad (9)$$

where

W_{18R} = no. of applications of 18-kip equivalent single-axle loads (ESALS),
RUT = rut depth (in.),
THICK = thickness of aggregate surface (in.),
E_1 = modulus of aggregate surface (psi), and
E_2 = modulus of roadbed (psi).

In 1979, during the Low-Volume Road Conference in Ames, Iowa, a decision was made to incorporate this algorithm as a manual procedure in the "new" Chapter 50 (*17*). This and the development work to computerize the entire design process were completed in 1983. During the ensuing 5 years, significant changes in computer technology and existing design methods (1986 AASHTO guide) prompted the Forest Service to reevaluate the situation. In 1988 the Surfacing Design Evaluation Report (*2*) was written for internal use and discussion and recommended the following:

1. Adopt the revised 1986 AASHTO design guide and the companion program (DNPS86/PC) for bituminous-surfaced roads,
2. Develop a surfacing design guide for aggregate-surfaced and unsurfaced roads using existing technology, and
3. Incorporate the concept of multiple user levels into the design process (the user levels imply differing levels of complexity of operation and variability of design).

USFS Region 8 ARMS Method

ARMS is a road surfacing design method developed in Region 8 of the Forest Service (Scholen, unpublished data). It was a result of the need for an aggregate management system suitable for a regionwide situation in which there were many isolated, low-cost, short road segments. The ARMS surfacing design procedure utilizes existing geologic data (such as state geological maps) as an index to soil properties for input to surface design equations. Because of oil and gas exploration over much of Region 8, detailed geologic maps are available. The maps separate rock formations into units of similar petrographic characteristics, and these characteristics are then correlated to engineering properties of soils. In this way, the maps are used to establish a geotechnical data base for use in ARMS. In addition, regression equations developed from correlated laboratory data are used to supplement traditional sampling and testing techniques.

The thickness design is based on the SDMS manual equations. Two criteria are used—rut depth and serviceability loss. The design equation based on rut depth is

$$W_{18RUT} = 64.51 * (t_p)^{-1.4665} * [3 (TSI)^{-0.5}]^{2.575} * \log t^{5.155} * \left(\frac{E_B}{1{,}800}\right)^{3.434} * \left(\frac{E_{SG}}{1{,}800}\right)^{1.048} \quad (10)$$

where

W_{18RUT} = no. of applications of 18-kip ESALs,
t_p = tire pressure (psi),
TSI = terminal serviceability index,
t = thickness of aggregate surface (in.),
E_B = resilient modulus of aggregate surface (psi), and
E_{SG} = resilient modulus of subgrade (psi).

Equation 10 is very similar to the SDMS manual rutting equation (Equation 9). It can be seen that the last three terms are the same. The rut depth term in Equation 9 was replaced with an expression that uses terminal serviceability index instead. Region 8 has developed Table 2, which relates the rut depth as a function of Traffic Service Level (TSL). The appropriate TSI and its corresponding allowable rut depth are selected from Table 2 and entered into Equation 10.

The other criterion used in this design procedure is serviceability loss, and this is identical to the SDMS Equation

TABLE 2 SERVICEABILITY INDEX AND RUT DEPTH

TSL	PSI	TSI	MRD
A	4.7	2.0	2.1
B	4.2	1.5	2.4
C	3.5	0.5	4.2
D	3.5	0.25	6.0

Notes:

TSL = Traffic Surface Levels
PSI = Present Serviceability Index
TSI = Terminal Serviceability Index
MRD = Maximum allowable rut depth

8. The ARMS program allows the user to enter resilient modulus data for both aggregate and subgrade layers, if available. If these are not known, a set of default values is available for different soil types such as crushed limestone, limerock, and sand clay. Initially, moduli were calculated on the basis of CBR using the following equation, which is found in SDMS:

$$M_R = 1{,}800\text{CBR}^{0.7} \quad (11)$$

where M is the resilient modulus in pounds per square inch and CBR is the California bearing ratio.

In 1986 laboratory testing was performed on typical aggregates used in Region 8 to verify the assumed values. In most cases, the values were verified, but some were modified to reflect the laboratory results. Variations in rainfall are also considered through the number of rain days a month. Traffic is assumed to be uniform throughout the month, but the program will consider rainfall effects (and therefore weaker subgrade) in its design based on the amount of traffic hauled during rainy days. The default tire pressure is 80 psi, but other values may be entered, with the recognition that the higher tire pressures drastically increase the rate of surface failure.

AASHTO Low-Volume Road Design Method

The AASHTO (1986) design guide presents graphical solutions based on the SDMS manual equations (Equations 8 and 9). No modifications were made to these equations apart from converting them to nomographs. Figures 5 and 6 show the two nomographs used for design.

However, aggregate loss has been considered. If aggregate loss is significant, an estimate may be made and added to the aggregate thickness:

$$D_{BS} = \overline{D}_{BS} + (0.5 \times GL) \quad (12)$$

where

D_{BS} = total thickness of aggregate layers (in.),
$\overline{D}_{BS}$ = thickness of aggregate layer based on rut depth or serviceability loss (in.), and
GL = estimated gravel loss over performance period (in.).

USFS Chapter 50 Design Method

The current version of Chapter 50 was developed in 1974 and last revised in May 1982 by the office in Region 6 (*1*). The 1982 version was intended as an interim measure until SDMS was completed. Two sources were used to develop the design procedure. The first is the Corps of Engineers, specifically the work done by Hammitt (*6*) on unsurfaced roads described previously. Hammitt's work involved the construction of unsurfaced test sites and the development of a modified *f*-factor through regression analysis. The failure criterion used was a 3-in. rut depth. On the basis of the same data, the Forest Service then similarly developed a modified *f*, but used a 2-in. rut depth as the failure criterion instead. The modified *f* that was obtained is

$$f = 0.216 \log C + 0.1705 \quad (13)$$

where C is coverages.

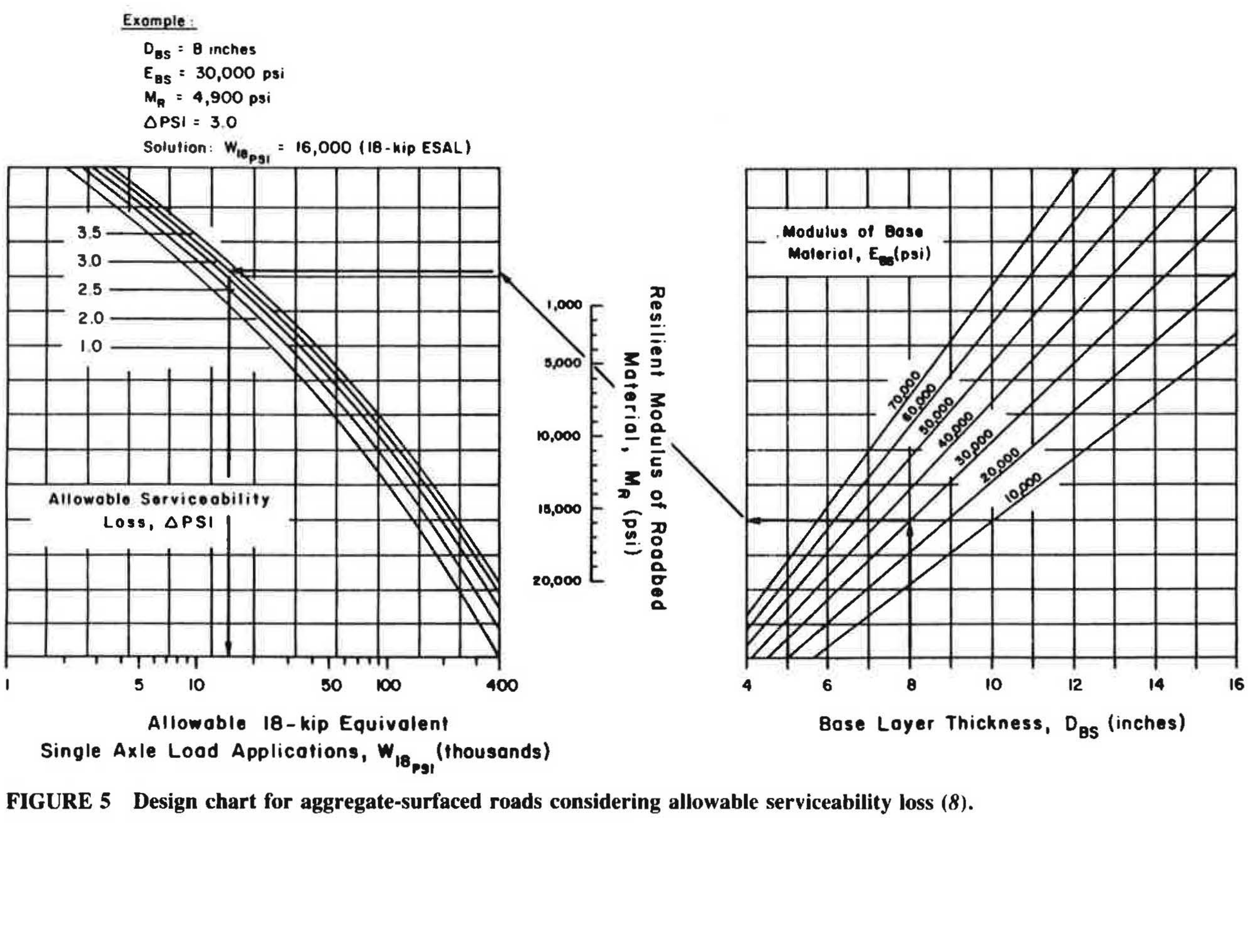

FIGURE 5 Design chart for aggregate-surfaced roads considering allowable serviceability loss (*8*).

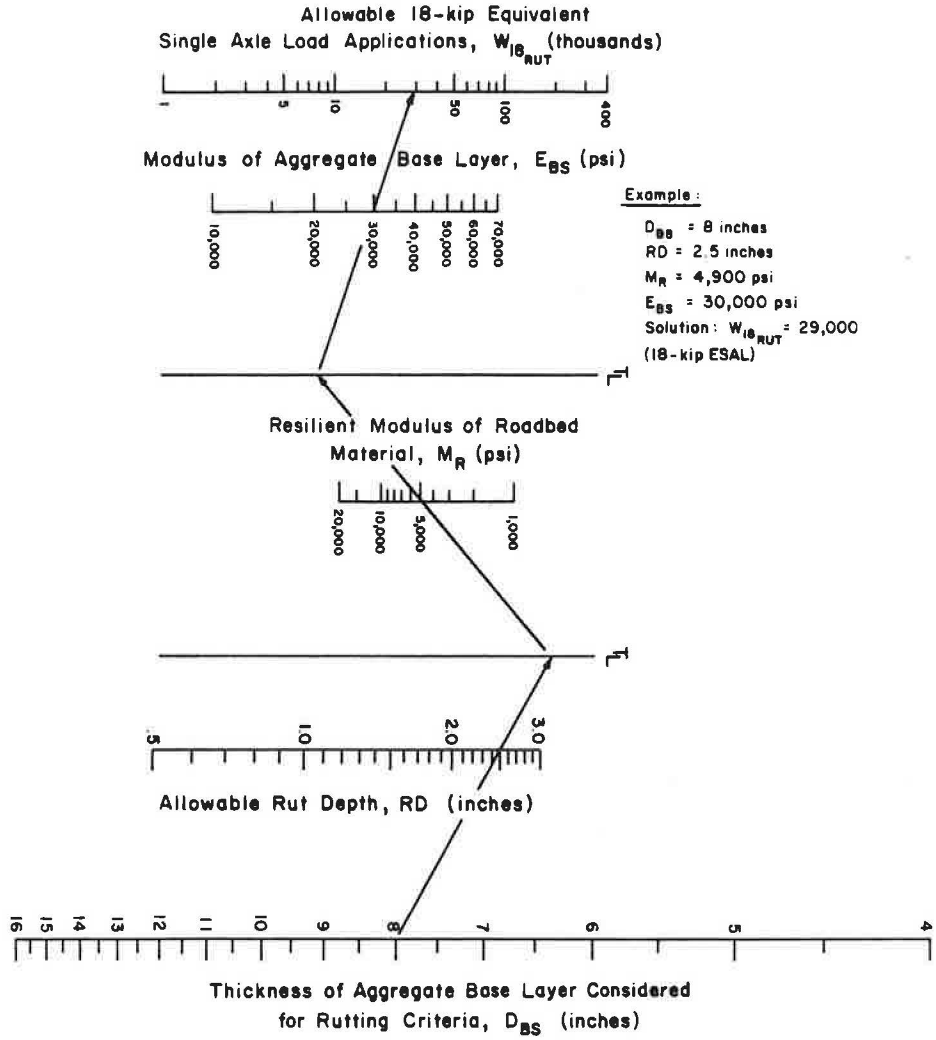

FIGURE 6 Design chart for aggregate-surfaced roads considering allowable rutting (*8*).

The other source for the design method came from the AASHTO Interim Guide (*10*), originally published in 1972 and subsequently revised in 1981 (the Blue Book). The procedure for determining the weighted structural number was incorporated into Chapter 50 in 1974 with minor modifications to the nomograph. Specifically, the modifications were aimed at extending the scale for the regional factor (R) to include values greater than 5. The design equation for this nomograph is as follows:

$$\log W_{t18} = 9.36\log(\text{SN}+1) - 0.20 + \frac{G_t}{0.40 + \dfrac{1{,}094}{(\text{SN}+1)^{5.19}}} + \log\frac{1}{R} + 0.372(S - 3.0) \qquad (14)$$

where

W_{t18} = total applications of 18-kip ESALs,
SN = structural number,
S = soil support value,
R = regional factor, and
G_t = $\log[(4.2 - P_t)/(4.2 - 1.5)]$ where P_t is the terminal serviceability index.

Figure 7 was then developed for a given aggregate layer coefficient (a) of 0.14. The curved lines represent the Corps equations (1, 2, and 3), and the straight diagonal line is that from AASHTO (Equation 14). The curve giving the lesser aggregate thickness controls. If material with a lower layer coefficient is used, the depth must be adjusted using the following equation:

$$\text{SN} = a_1D_1 + a_2D_2 + \ldots \qquad (15)$$

where

SN = structural number,
a_i = layer coefficient for the ith layer, and
D = thickness of ith layer

This last step is an unusual feature of this method, particularly if the controlling thickness was originally determined using the Corps equation.

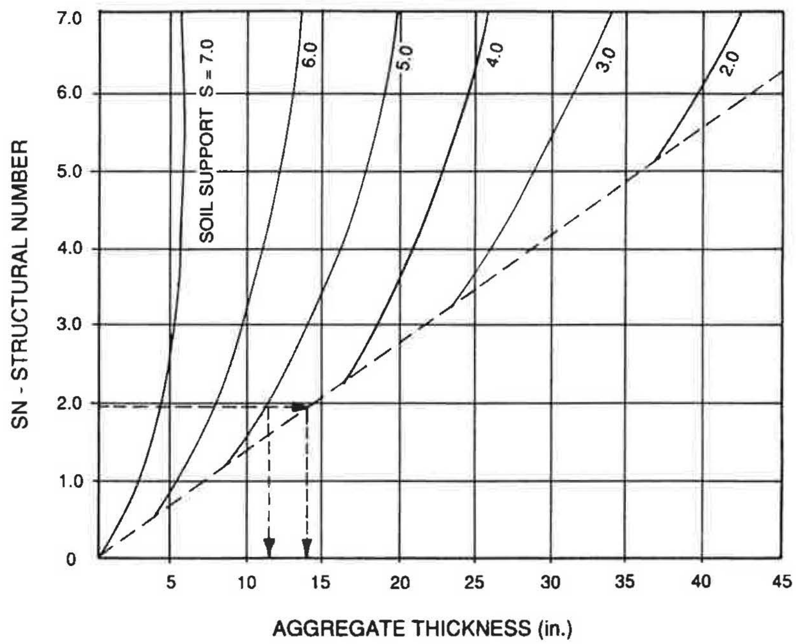

FIGURE 7 Design chart for aggregate-surfaced pavements (*1*).

USFS Region 1 Seasonal Surfacing Method

In 1980 Region 1 of the Forest Service developed a design procedure for aggregate roads based on seasonal haul (*24*). This was referred to as the Region 1 Supplement No. 10 to the Forest Service Handbook (FSH 7709.11), Chapter 50. The modifications considered seasonal variations in subgrade soil strengths in the design of aggregate-surfaced roads. The modifications could be used for shutting down haul during spring thaw, restricting haul to dry or frozen subgrades, or compacting subgrades to exceed standard specifications. In addition, a terminal serviceability index of 0 instead of 2 was used in the design charts.

Two studies were used to monitor subgrade soil conditions and the performance of aggregate-surfaced roads. The results were used to obtain a relationship between percent saturation of the subgrade and time of the year. First, a relationship was established between subgrade soil strength, percent saturation, and percent compaction (by laboratory testing). Next, the seasonal variation in percent saturation throughout the design period (usually one year) was estimated from field data. Finally, the design period was divided into time periods of similar percent saturation and a CBR assigned to each increment.

Once the above steps have been completed, the aggregate thickness may be estimated for the anticipated hauling season. These roads designed with this method are for use only during certain times of the year, and are not all-weather roads. They will appear to fail prematurely if used for circumstances other than those considered in the design. Also, the procedure was developed primarily to restrict haul to periods when the subgrade is strongest; therefore, the converse (i.e., design for when subgrades are weakest, such as during spring thaw) may not necessarily be a valid design approach.

Willamette National Forest "Seasurf" Design Method

The Willamette design method (unpublished data, 1988) was also modified from the original Chapter 50 (*1*). The modifications incorporated seasonal changes in subgrade soil strengths and traffic. In addition, Miner's hypothesis is used to sum up damage ratios in the design of aggregate thickness. The procedure is very similar to that described for Region 1, if not the same. The regional factor used, however, is different for the Willamette. In addition, Region 1 uses a terminal serviceability index of 0, while the Willamette uses 2 or 1.

FHWA Report

Alkire (*9*) recently published a report sponsored by FHWA for the design and operation of aggregate-surfaced roads. For aggregate thickness design, Alkire provides three levels of design complexity—A, B, and C—with C being the least complex and A the most complex. Each level utilizes design methods that have generally been discussed previously. Therefore, only the key elements of the design will be highlighted.

Level C Design

The Level C design uses the rut depth model developed by Hammitt (*6*) and is the simplest design procedure. Alkire assumes that the coverages are equal to passes and that the equivalent single-wheel load is 9,000 lb for an 18-kip axle load. Implied in the use of this equation is the acceptance of the 3-in. rutting failure criterion. The procedure was further simplified when he suggested that the effect of traffic could be removed and thickness could be calculated using

$$t = (750/\mathrm{CBR})^{0.5} \quad (16)$$

Level B Design

The Level B design is the AASHTO procedure taken from the 1972 Interim Guide (*10*). Figure 8 shows the relationships developed between 18-kip ESALs and structural number for various soil support values. To develop this chart the following assumptions were made: initial serviceability = 4.2; terminal serviceability = 1.5; and regional factor = 1. By using this chart, traffic may be calculated for a given thickness or thickness can be determined from estimated traffic. The relationship between structural number and thickness was shown previously in Equation 15. Tabular values are also provided to adjust the layer coefficient on the basis of the strength of the granular material. In addition, guidance is given for the calculation of soil support and *R*-values.

Level A Design

The Level A design consists of the manual equations (Equations 8 and 9) from SDMS. Although aggregate loss is mentioned as a factor that needs to be incorporated into the design, no guidance is given regarding methods for estimating this factor.

Finally, Table 3 is a summary of all the design methods reviewed and their respective equations.

Aggregate Loss

Aggregate loss and its prediction are important factors in aggregate surfacing design and maintenance. One equation that was used in the 1977 version of LVR was developed by Lund (*25*) and is as follows:

$$\mathrm{GL} = 0.162 + 0.0188(\mathrm{LT}) + 0.0382(\mathrm{F/C}) - 0.00110(\mathrm{TTU}) - 0.00213(\mathrm{P3/4}) \quad (17)$$

where

GL = aggregate loss corrected for settlement (ft),
LT = number of load logging trucks (000s),
F/C = fill or cut section (fill = 1.0, side cast slope = 1.5, cut = 2.0),
TTU = total two-way traffic units (000s) (one non-truck = 2TTU, one logging truck round trip = 10 TTU), and
P3/4 = percent of road surfacing sample smaller than 0.75 in. in diameter.

Later this equation was simplified in the 1979 LVR version to

$$\mathrm{GL} = 0.1 + 0.01019(\mathrm{LT}) \quad (18)$$

where terms are as identified above (*25,26*). A good discussion of the Lund equations is contained in the report by McCullough and Luhr (*18*).

Equation 18 was used in SDMS. In addition, the SDMS user's manual provided other equations that could be used to calculate the aggregate loss manually. The first equation was developed in Brazil and the second in Kenya. The Brazilian equation is

$$\mathrm{GLIN} = \frac{B}{25.4}\, 0.0045(\mathrm{LADT}) + \frac{3{,}381}{R} + 0.467(G) \quad (19)$$

where

GLIN = aggregate loss during time period considered (in.),
B = number of bladings during time period considered,

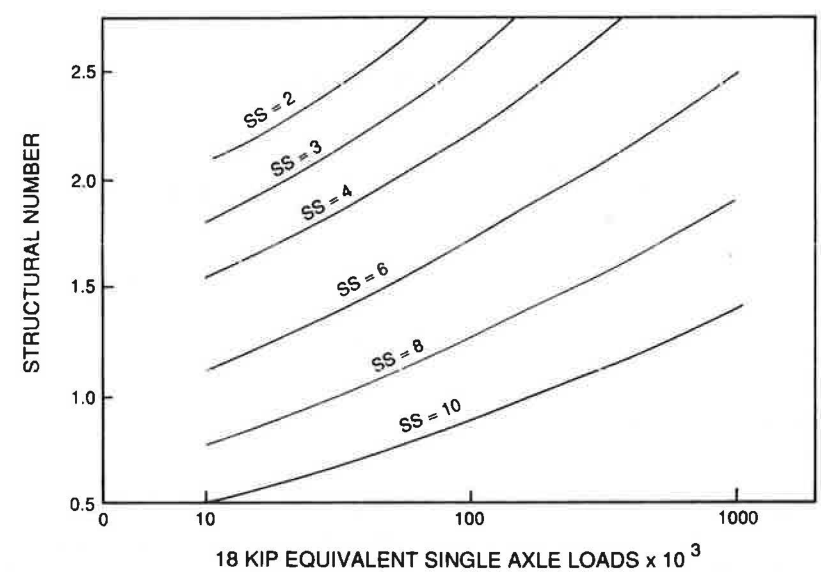

FIGURE 8 Structural number for various 18-kip equivalent axle loads and soil support values (*9*).

TABLE 3 SUMMARY OF DESIGN EQUATIONS

Methods	Design Equation	Design Criteria
Corps of Engineers		
Hammitt (1970) *(6)*	Equation 4	Rut Depth
Barber et al. (1978) *(5)*	Equation 5	Rut Depth
Draft TM 5-822-30 (1988) *(7)*	Equation 6	Unknown
USFS		
Region 4	Equation 7	Rut Depth
SDMS (Manual Equations)	Equation 8	SI
	Equation 9	Rut Depth
Region 8 (ARMS)	Equation 10	Rut Depth & SI
Chapter 50	Equation 13	Rut Depth
	Equation 14	SI
Region 1	Chapter 50 w/modifications	SI
Willamette NF	Same as Region 1	SI
FHWA		
Level A	Same as SDMS Manual Equations	
Level B	Figure 8	SI
Level C	Equation 16	Rut Depth
AASHTO	Same as SDMS Manual Equations	

SI = Serviceability Index

LADT = average daily traffic in design lane (for one-lane road use total traffic in both directions),
R = average radius of curves (ft), and
G = absolute value of grade (%).

The Kenyan equation (*27*) may have more applicability in situations where logging activity is relatively minor:

$$AGL = f\left(\frac{T^2}{T^2 + 50}\right) * 4.2 + 0.092(T) + 0.0889(R^2) + 1.88(VC) \quad (20)$$

where

AGL = annual aggregate loss (in.),
T = annual traffic volume in both directions of vehicles (000s),
R = annual rainfall (in.),
VC = average percentage gradient of the road, and
f = 0.037 for lateritic gravels, 0.043 for quartzitic gravels, 0.028 for volcanic gravels, and 0.059 for coral gravels.

Recent research in South Africa (*28*) has provided another relationship for aggregate loss:

$$GL = D[ADT(0.047 + 0.0027 * N - 0.0005 * P26) - 0.365 * N - 0.0014 * PF + 0.048 * P26] \quad (21)$$

where

GL = gravel loss;
D = time period under consideration (days/100);
ADT = average daily traffic;
N = Weinert N-value (related to three climatic levels; precipitation and evaporation are related to the geotechnical behavior of the materials);
PF = plastic limit × percent passing 200-mesh sieve (P75); and
P26 = percent passing the 26.5-mm sieve.

Finally, Paterson (*29*) has reviewed a number of gravel loss relationships. Table 4 shows a comparison of gravel loss rates from various studies for a range of gradient and rainfall. As can be seen, using data from other studies for the Forest Service situation can be risky, particularly for Region 6. The combinations of gradient and rainfall do not begin to resemble the road network in Region 6. Gradients of 6 to 8 percent are common, together with annual rainfalls of 1500 to 2500 mm. Paterson has included a general model to include the major traffic, gradient, and rainfall effects, but material properties are excluded:

$$GL = (30 + 180 * MMP + 72 * MMP * G) * h * ADT * \Delta t * 10^{-5} \quad (22)$$

where

GL = surface material loss (mm),
MMP = mean monthly precipitation (m),
G = average longitudinal gradient (%),
h = proportion of heavy vehicles in traffic (fraction),
ADT = average daily traffic (vehicles/day),
Δt = time period (days).

TABLE 4 COMPARISON OF GRAVEL LOSS RATES FROM VARIOUS STUDIES (29,30–34)

Study Location	Units	Rate of gravel loss (mm per 100,000 vehicle units) for gradient (%) and annual rainfall (mm/yr): 0%, 1,000	0%, 2,000	3%, 1,000	3%, 2,000	Percentage heavy vehicles
Brazil	V	30	32	39	43	50
Ghana	HV	(20-100)	(10-60)	40-160	(30-60)	–
	V	30	13	41	26	50
Oregon	AV	–	–	–	(240)	100[1]/
	V	–	–	–	(40)	50
Kenya A	V	(7)	(21)	(12)	(60)	(35)
	V	10	30	17	86	50
Kenya B	V	10	29	16	82	–

[1]/ Assumed value.

Notes: V = per 100,000 vehicles; HV = per 100,000 heavy vehicles when light vehicles are present but not counted; AV = articulated logging vehicles, rated as AV = 3, HV = 6, V. -. Not available. ( ). Original data not adjusted for vehicle mix.

The general effects of material properties are understood to behave as follows:

1. Increasing the plasticity index reduces the loss rate (Brazil, Ghana),
2. Increasing the relative compaction of the surfacing reduces the loss rate significantly (*25*), and
3. Coral gravels have 40 percent higher loss rates than lateritic, quartzitic, and sandstone gravels, which in turn have 40 percent higher loss rates than volcanic (vermicular) gravels (Kenya).

EVALUATION OF DESIGN METHODS

The Forest Service evaluation report of June 1988 (*2*) provided the majority of the evaluation criteria used in this paper. These criteria may be expressed as a series of questions:

- Is the design procedure valid for aggregate-surfaced and earth roads?
- Are the inputs expected to have a major role in pavement deterioration?
- Are standard traffic units (e.g., 18-kip ESALs) used?
- Can tire pressures be varied?
- Is the material characterization "reasonable"?
- Are risk and reliability concepts considered?
- Can failure criteria levels be changed?
- Is seasonal haul incorporated into the design?
- Has there been any field experience?

The one criterion not included in the Forest Service report list that is included above is the validity of the design method. These items are discussed further in the following paragraphs.

Validity

The validity of the design method for either aggregate-surfaced or earth roads is probably the most important attribute to be considered. By validity is meant whether the basis of the development of these design procedures is appropriate for their purpose. As an example, it could be considered inappropriate to design an aggregate-surfaced road using algorithms developed from earth road data or asphalt-surfaced road data.

Input Variables

The type and quantity of input variables are critical to the success of any design procedure. Inputs that are reasonable and recognizable to the road designer, such as CBR to describe soil strength, are highly desirable. They should be in standard units of measurement and should also be readily available. Inputs such as the internal angle of friction and approach speed of a vehicle behind a grader are either difficult to obtain, esoteric, or may seem completely unrelated to the problem at hand. The consequence of such inputs is a decrease in the usefulness of the design method to the engineer or road manager.

Traffic

Traffic data used should be in standard units, such as 18-kip ESALs, or in a format that may be easily modified to ESALs, such as timber volume (board-feet). Some design methods use units that are not easily converted into ESALs, such as the Corps of Engineers Design Index (DI). The number of repetitions versus coverages should also be noted, because they may not necessarily mean the same thing.

Tire Pressures

In recognition of the fact that a wide range of tire pressures (as wide as 50 to 150 psi) may be used in trucks, design procedures should be able to incorporate this feature. This is particularly important because high tire pressures have a dramatic effect in the deterioration of pavements. In addition, the Forest Service is currently conducting the Central Tire Inflation (CTI) study, which is evaluating the effects of low tire pressure on forest roads. It would be useful if the results of this study could be incorporated into the selected design procedure.

Materials Characterization

It is desirable that the materials used in the road structure be characterized in units of measurement that are standard and easily quantifiable. An example would be the use of the soil support value (*S*) or resilient modulus for soil strength, because these are widely known and may be available. Atterberg limits, although also a standard unit of measurement in soil mechanics, cannot be considered a standard parameter for the determination of soil strength in the design of roads.

Risk and Reliability

Risk and reliability may be defined in many ways. However, to evaluate the different procedures, the question posed was, "Are risk and reliability explicitly incorporated into the design method?" Currently, only the SDMS computer algorithms and the Barber et al. (*5*) models contain this variable. Reliability, as defined by AASHTO (*35*), is the probability that designed pavement sections will withstand the actual number of ESALs that will be applied over the design period. The method used by AASHTO is to apply a reliability design factor, F_R, to the design traffic and in this way modify the thickness requirements.

Failure Criteria

The failure criteria used in most of these design methods are either rut depth or serviceability loss. An additional criterion used in several other design methods is aggregate loss. Some design procedures have developed design equations that assume a given failure level such as a 2-in. rut depth, and these may not be modified. In other methods, the failure levels are variables and may be changed very easily. It would be desirable to have the ability to make these changes.

Seasonal Haul

The concept of seasonal haul was developed in an effort to recognize that some forest roads are only open for use during certain times of the year. An example would be log haul during the summer months only, with the same road being closed during spring thaw. Therefore, designing such a road for the strongest time of the year instead of the weakest would greatly decrease the aggregate thickness required. Currently, only a few design methods explicitly consider this.

Field Experience

Field experience is simply a question of whether each design method has actually been used for design in the field. However, it should be noted that some procedures such as the AASHTO (*8*) guides receive such wide distribution all over the United States that it is not possible to determine if they have been used in design. The answers to this question are therefore only accurate to the best of the authors' knowledge.

Rating Scheme

Table 5 is a summary of all the aggregate surfacing design procedures included in this synthesis and their evaluation. Each of the nine attributes used for the evaluation have been discussed in the preceding paragraphs. The evaluation procedure was deliberately kept simple; therefore, weights were not assigned to each attribute. If a design method contained a particular attribute, it received a plus and if it did not, it received a minus. For those that fall within the grey zone between a yes and no answer, a zero is given. The pluses and minuses are then added together to arrive at a total score.

As can be seen from Table 5, two procedures have the highest score of +2: the Corps 1978 work by Barber et al. (*5*) and the Region 8 ARMS program. Note that the procedure by Barber et al. has more pluses than the ARMS program, although it also has more minuses. The Technical Advisory Board's opinion was that the pluses outweighed the minuses; therefore, the equation by Barber et al. was selected over ARMS.

Conclusions

To recapitulate, the direction for this project was to select the best available design method for use on forest roads. As noted, virtually all the design procedures reviewed, including that judged best by the Technical Advisory Board, have not been field verified. Field trials will be needed to validate the selected procedures, regardless of which procedure has been selected.

Earth Roads

At one time it was anticipated that Hammitt's (*6*) 1970 equation (Equation 4) relating thickness to coverages and wheel load would be most appropriate for the earth road design. However, the most important information sought by the designer is a prediction of either maintenance requirements or environmental damage resulting from allowing vehicles to operate directly on the native materials. Hammitt's 1970 equa-

TABLE 5 EVALUATION OF DESIGN METHODS

ATTRIBUTES	COE - 1988 TM 5-822-3 (7)	FHWA (C) COE - 1970 (Hammitt) (6)	Region 4 COE - 1978 (Barber et al.) (5)	R - 8 ARMS	SDMS - Manual AASHTO - 1986 FHWA (A) (8)	SDMS Computer	USFS Chap. 50 (1)	Region 1 Willamette	FHWA (B) (AASHTO 1972) (10)
1a. Validity for Aggregate Roads	+	-	+	0	0	-	-	-	-
1b. Validity For Earth-Roads	-	+	+	-	-	-	-	-	-
2. Inputs Make Sense	+	+	+	0	0	-	+	+	+
3. Standard Traffic Units	-	-	-	+	+	+	+	+	+
4. Varying Tire Pressure	+	+	+	+	-	-	-	-	-
5. Material Characterization	+	+	+	+	+	-	0	0	+
6. Risk/Reliability	-	-	-	-	-	+	-	-	-
7. Change failure criteria	-	-	+	+	+	+	-	-	-
8. Seasonal Haul	-	-	-	-	-	+	-	+	-
9. Field Experience	-	-	-	+	0	-	+	+	-
SCORE	-2	-2	+2	+2	-1	-2	-3	-1	-4

tion simply did not provide the means to estimate these maintenance needs or resource impacts. Consequently, the equation by Barber et al. (*5*) (Equation 5) was selected to predict total rut depth for the earth road situation, with some modifications.

Aggregate-Surfaced Roads

On the basis of the evaluation performed and after much discussion with the Technical Advisory Board, the equation by Barber et al. (*5*) was selected as the thickness design algorithm (Equation 5). It is recognized that the algorithm has some rather serious limitations. Perhaps the most serious is that the algorithm has little, if any, field experience. However, this is also true for most of the design algorithms reviewed. Equation 5 was developed at WES through a review of previous field data. The intent during the development was to provide a relationship as a starting point that could be refined through field experiments and experience in use.

A second major reservation that surfaced as a result of the evaluation was that the design algorithm appeared to underpredict thickness requirements for low-strength subgrade situations that might simulate wet weather haul. In spite of the shortcomings and reservations, this design algorithm was selected for the following reasons:

1. The design algorithm contains most of the design factors believed to be most important by the Forest Service.
2. The equation is stable with respect to the range of design inputs selected for use. The SDMS equation was unstable for some of the ranges of input values.
3. The algorithm was the most sensitive to changes in tire pressure, which was an input criterion. In addition, the thicknesses calculated were acceptable.
4. The design algorithm provided significantly reduced thickness requirements from those estimated through Chapter 50 for similar design inputs. This was consistent with the general perception that the Chapter 50 design method for aggregate surfaces is conservative.

In summary, there were clear reservations regarding the selection of the design algorithm. Unfortunately, the search of the existing thickness algorithms provided no clear choice, and it is the opinion of the Technical Advisory Board that the choice made was the best for forest road situations, given the state of the existing technology.

RECOMMENDATIONS

On the basis of the literature review and the analysis of the design methods in the preceding sections, the following recommendations are made:

1. For aggregate-surfaced and earth roads, the design algorithm selected was the model by Barber et al. (*5*) for aggregate-surfaced roads (Equation 5). The equation was slightly modified for use in the case of earth roads (the thickness of the compacted subgrade was assumed to be 6 in.).
2. One of the major disadvantages of many of the design procedures studied was their lack of field validation, particularly for forest road situations. Much of the test data that was used to develop many of the procedures was, as discussed earlier, from work done by the Corps in non-forest-related projects. In the development of SDMS, the Forest Service recognized this, and attempts were made to rectify this situation. It was anticipated that a data base from actual forest conditions could be used to validate or develop performance models for design of aggregate-surfaced and earth roads. However, for various reasons (e.g., insufficient traffic data) this was not successful. In the case of the Corps, projects to collect test data were also planned in cooperation with the Forest Service (*5*). However, they have not been followed up or the projects have been cancelled.

Therefore, the need for such field studies persists, regardless of whatever design method is selected. It is highly recommended that an attempt be made to gather some data that could be used to validate the selected design method and to enable future fine-tuning. Recognizing that data collection is expensive in time, money, and effort, it is suggested that good use be made of any existing studies with related data, such as the Central Tire Inflation project. In addition, data collection has to be flexible enough to accommodate changes in test sites. Finally, an attempt should be made to collect only data that are needed. This should include traffic; loads; subgrade and cover material strengths over seasons, particularly wet seasons; and the monitoring of the selected failure criterion. The effects of moisture on subgrade strengths are particularly important.

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