Procedure for Determining Capacity of Unrocked Roads

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Much of the concern over low-volume roads today is centered on the overdesigned standards, which cause high transportation costs. The objective of this study is to develop a procedure for evaluating the need for rock surfacing. The procedure considers the relationships among traffic demand, soil type, and precipitation. When the demand is seasonal, both soil and precipitation become major factors in determining the seasonal capacity of unrocked roads. In this study, these two factors were combined into a single composite measure, the number of shut-down days. The procedure developed was applied to determine the need for rock surfacing on 587.13 miles (939.41 km) of new single-lane roads proposed by a five-year timber sale action plan in the Gifford Pinchot National Forest, U.S. Department of Agriculture, Forest Service. The results indicated that the preferred alternative is to construct 122.61 miles (196.18 km) of aggregate roads and 464.52 miles (743.23 km) of dirt roads. When compared with the policy of building all rock-surfaced roads, this option of rock-surfacing selectively may save $12 million over the five-year period, or 20 percent of the total transportation cost, even if the forest pays $9 million to timber purchasers in compensation for the shut-down cost. The application demonstrated that such a process could be applied to developing regions, particularly where the traffic demand is seasonal.

In developing countries and in unpopulated areas of developed countries, a great deal of the transportation system is composed of gravel and native-surface roads. These two types of roads account for 39 percent and 28 percent, respectively, of more than 3 million miles of rural highways in the United States. With today's ever-tightening government budgets, the vast cost to construct, reconstruct, maintain, and operate this huge system becomes a major concern of the U.S. government. This concern was expressed by a panel consisting of representatives from local, state, and federal governments at the 61st Annual Meeting of the Transportation Research Board in Washington, D.C., in January 1982. The panel indicated that geometric standards for high-volume roads (1) are too high for low-volume roads and called for research in this area so that the road design standard and its construction cost can be reduced to a minimal level. This call aims to develop a cost-effective transportation system for low-volume roads.

The high transportation cost is also a major concern of the U.S. Department of Agriculture's Forest Service. In 1982, its budget for transportation amounted to nearly $600 million (note that all costs henceforth are quoted in U.S. dollars). A new Forest Service directive (2) calls for attention to the fact that "roads are often built at too high a standard, which creates more land disturbance and cost than is required to provide adequate, safe transportation." The Forest Service (by contract or through timber purchasers) annually builds some 7000 miles (11 200 km) of new (paved or rock-surfaced) roads within the national forests; if half of those new roads were single-lane and rock-surfaced and could provide adequate service for the harvesting and removal of the timber with limited or without rock surfacing, the Forest Service could potentially save from $50 million to $80 million each year by building lower-standard roads in the national forests. However, the road without rock surfacing or the road with limited rock is not operational when the subgrade is wet. The limitation of physical capacity and its impact on seasonal performance make many transportation planners and engineers think rock surfacing is a minimum requirement for building forest roads.

The objective of this study is to develop a procedure for evaluating the capacity of unrocked roads and determining the economic justification for rock surfacing. The procedure would lead to minimizing transportation cost without jeopardizing system performance. Its potential applicability has been demonstrated by the evaluation of a five-year timber sale action plan of the Gifford Pinchot National Forest in Washington State.

FACTORS RELATED TO USE OF UNROCKED ROADS

Two major factors that determine the need for rock surfacing are the time frame of use (all-weather versus seasonal) and the economic feasibility. A road with rock surfacing provides a riding surface that can better withstand the deleterious effects of traffic and environment; therefore it permits all-weather use. Its serviceability is higher, whereas its maintenance requirements are less than those of an unrocked road. In addition, its better surface quality also lowers the vehicle operating costs considerably. However, the unrocked road could save more than one-third of the long-term capital investment cost of construction.

In the national forests, most of the newly constructed roads are local roads, which are characterized as seasonal roads. The main purpose of local roads is to provide access for a particular timber sale. In many cases, they could be closed when the timber-harvesting activities are over. Because the traffic demand is seasonal, many local roads may not need rock surfacing. However, the quantity of demand is not the sole factor used to determine whether a road should be surfaced with rock or not. Among others are weather conditions, soil types, slope aspects, elevation, access to pit-run rock, local water tables, etc. During wet-weather periods, shutting down expensive logging equipment and crews would increase logging costs considerably. An option to avoid shutting down is to move the logging activity to an aggregate road. This would cause additional costs because of unrigging, moving, and rigging back up. This cost increases as the equipment becomes larger, more expensive, and more complex. The type of logging equipment should be considered before determining whether moving is desirable or building an aggregate road is preferred.

In certain areas of the Gifford Pinchot National Forest, for instance, the water table is quite high and the soil could retain moisture for long periods of time. In such areas, a very small amount and short duration of rainfall may require closure of an unrocked road. On the other hand, there are higher-elevation areas that have a southeastern aspect and soils that contain a high percentage of rock or pumice and have a lower water-holding capacity. In these areas, a very heavy rainfall for a longer duration will have little or no effect on the road surface. As indicated previously, from the point of view of vehicle operation, aggregate roads are preferred. If pit-run sources were located closer to the project and the existing pits were better utilized, the rock cost could be significantly reduced. A lower rock cost may favor rock surfacing economically.

EVALUATION PROCESS

Based on the foregoing discussion of factors influencing the need for rock surfacing, an evaluation process was developed for use by the Gifford Pinchot

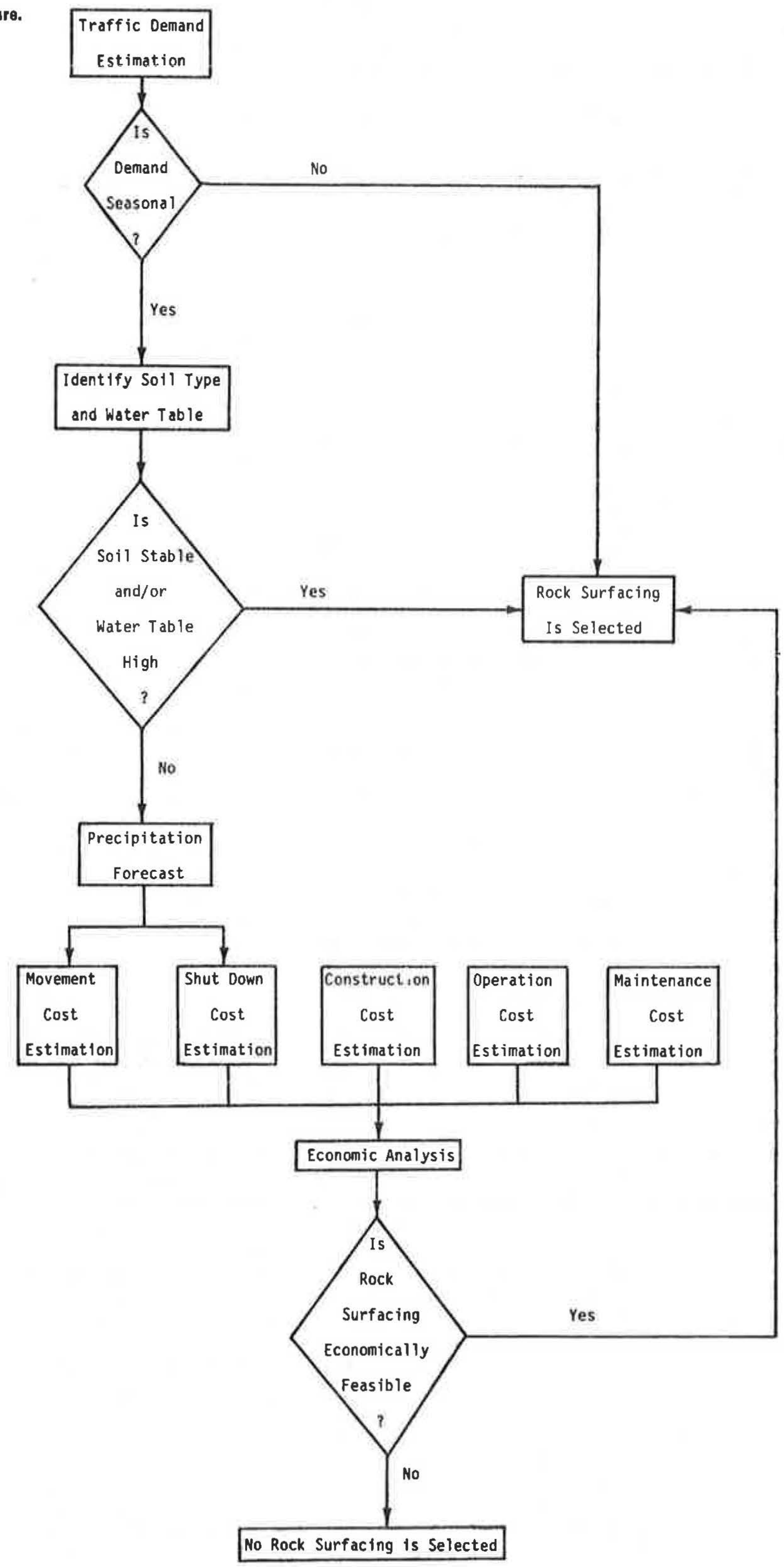
National Forest. It consists of the following steps:

1. Traffic-demand estimation;
2. Identification of soil type and water table;
3. Forecast of precipitation;
4. Estimation of cost of vehicle operation, road construction, road maintenance, and equipment shutdown and movement; and
5. Economic analysis.

The sequence of these steps is shown in Figure 1.

The first step is to estimate the traffic demand in terms of traffic volume and its temporal distri-

Figure 1. Road-surfacing evaluation procedure.



bution. If the volume is high and its distribution is not heavily concentrated on a certain period of the year, the need for surfacing is apparent. However, if the result of step 1 indicates that the demand does not necessarily require a rock surfacing, step 2 may be performed to identify the soil type and water table. If the soil is unstable, rock surfacing may be needed in order to reduce the maintenance cost. If the water table is high and the soil could retain moisture for a long period of time, rock surfacing is also necessary. Otherwise, the construction of unrocked roads is considered to be one of the options. Step 3 is to estimate the number of days with high precipitation. During this wet period unrocked roads become unoperational and the logging activity is forced to shut down. Step 4 is to estimate the savings and costs as a result of selecting an unrocked road. They include the cost of road construction, road maintenance, vehicle operation, and logging equipment shut-down and movement. Based on the results of the preceding steps, step 5 is to perform an economic analysis for determining the economic feasibility of rock surfacing.

In the evaluation procedure, the first two steps and step 4 are straightforward, whereas step 3, the precipitation forecast, and step 5, the economic analysis, are discussed in detail in the following sections.

Precipitation Forecast

In precipitation forecasting, an attempt is usually made to determine the probability of a given duration or the accumulation of a given amount of precipitation during a given period at a specified point. These two variables, along with soil type and road location with respect to aspect, are major factors influencing the physical capacity of unrocked roads. The joint effect of these factors can be used to determine when the ground will be too wet to be operational and an unrocked road must be shut down and when the road will dry up and become operational again. Since the investigation of interaction between these factors is beyond the scope of this study, the number of shut-down days was used as an indicator of unrocked-road seasonal capacity. The shut-down days are determined by the accumulated amount of rainfall, the duration of precipitation, and the soil type (3).

In order to forecast the probability that a certain number of shut-down days will occur during the timber haul season, one may adopt either of two procedures. One may rely on past experience with similar situations and assume that future results will be approximately the same, or one may analyze the various ways in which the shut-down period can happen or fail to happen and thereby compute a theoretical probability. The former method is that of statistical probability, which has considerable value and utility in connection with statistics; the latter method has given rise to mathematical probability. In probability, the contributing factors are known, but a result can never be predicted with absolute certainty. In statistics, the end product is known, but the causes are in doubt. The statistical method was selected for use in this study because long records of data from observations are available on the national forest and local factors are considered to be important for the forecast (4).

There are many statistical techniques that can be used to forecast shut-down days, such as log-normal, Pearson type III (gamma), log-Pearson type III distributions, and large-scale numerical forecast models (4-7). The one-sided hypothesis test was selected for use in this study because it is simple and allows estimation for various one-sided confidence intervals of μ. The null hypothesis is

$$H_0 : \mu > \bar{X} - t_r(s/\sqrt{n}) \quad (1)$$

where

$\bar{X}$ = sample mean,
t_r = t-coefficient at r percent one-sided confidence interval,
s = standard deviation of sample, and
n = sample size.

Equation 1 is against the one-sided alternative hypothesis (H_1); that is,

$$H_1 : \mu < \bar{X} - t_r(s/\sqrt{n}) \quad (2)$$

Based on the above hypothesis test, the number of dry days can be estimated for a given r percent one-sided confidence interval; that is,

$$\bar{X} < \mu + t_r(s/\sqrt{n}) \quad (3)$$

Economic Analysis

The economic justification for selecting unrocked roads is that the savings of road construction are equal to or larger than the sum of costs as a result of no surfacing. The cost items include vehicle operation, road maintenance, road construction, and logging activity shut-down and logging equipment movement. The relationships between these cost items are expressed by

$$Y > X_1 + X_2 + Z_1 \qquad Y > X_1 + X_2 + Z_2 \quad (4)$$

where

Y = difference in road construction cost be tween aggregate and dirt roads,
X_1 = difference in vehicle operating cost,
X_2 = difference in road maintenance cost,
Z_1 = QA + M = cost as result of moving,
Z_2 = QB = cost as result of shutting down,
Q = cost per day including logging equipment and crew,
A = days required for moving,
M = fuel cost for moving equipment, and
B = number of shut-down days.

The major factor affecting the difference in vehicle operation costs between aggregate and dirt roads is roughness. A high degree of roughness would reduce vehicle speed and increase travel cost. This becomes critical if the demand approaches or exceeds the capacity. An examination was made for a single-lane dirt road with turnouts, +5 percent grade, fair alignment, and no ditch. The average operation speed under these conditions is 14 mph (22.4 km/h) (8). According to R. Kurtti of Mt. Hood National Forest (April 6, 1980), in their experience, the average daily traffic (ADT) for a single-lane road with a 14-mph average speed is 88 vehicles/day. Assume that on the new road the recreation travel is restricted and the administrative and supporting vehicles account for 25 percent of traffic. With these assumptions, the ADT for logging trucks is about 66 vehicles/day and half of that traffic is loaded. With the further assumption of 5 mbf (11.8 m^3) per truckload, the average daily capacity of the given single-lane dirt road allows hauling 165 mbf (389.4 m^3) of timber. On the other hand, with the assumptions of harvesting 1 million board feet (mmbf) (2360 m^3) per month and a five-day work week, the average daily timber production is 50 mbf (118 m^3). The traffic demand is less than one-third of the road capacity. Thus road capacity does not appear to influence the cost of operation. However, a higher degree of roughness of dirt roads could increase operating cost approximately 8 percent (8).

It should be noted that Equation 4 does not account for all benefits of an unrocked road in the national forest. Based on the rule of thumb that each mile of access road constructed takes about 5.5 acres of timberland out of production, this acreage will never be restored for producing timber when an aggregate road is constructed. Also, in many cases a dirt road may not become productive land, but it can be altered in some way to meet most or all of several objectives: (a) to reduce or eliminate soil erosion, (b) to reduce the cost of maintenance when the road is not in use, (c) to provide forage for cattle or big game, (d) to reestablish the natural appearance of the land occupied by the road, and (e) to prevent or discourage motor vehicle use after the road has served its original purpose. All the aforementioned objectives are the advantages of constructing an unrocked road rather than an aggregate road and were not used as evaluation parameters.

CASE STUDY

The evaluation procedure developed was applied to a five-year timber sale action plan (1981-1985) of the Gifford Pinchot National Forest to determine the need for rock surfacing. In the evaluation procedure, the first step was to determine the traffic demand in terms of new construction based on the proposed timber-sale volumes and existing road systems. Among the 305 projects proposed for the five-year action plan, 24 projects do not have transportation plans and 50 projects do not require new road construction. The remainder of the 231 projects require new road construction that ranges from 0.2 to 13.3 miles (0.32-21.28 km).

After the traffic demand had been estimated, the next step was to identify soil type and water table. Based on the identified soils and water tables, 34 of the 231 projects were found to need rock surfacing because their water tables are high and soils may retain moisture for a long period of time, which could jeopardize the scheduled timber harvesting. Thus the projects on which there may be an option for constructing unrocked roads are reduced to 197. These projects have 1456.6 mmbf (3 437 596 m^3) of timber scheduled for harvesting and require 538.25 miles (861.20 km) of new roads. They are shown in Table 1.

The third step of the evaluation procedure was to forecast the number of shut-down days that would occur if unrocked roads were constructed. It was assumed that the amount of precipitation per day, which ranged from 1 to 2 in (2.54-5.08 cm), would require two shut-down days and that exceeding 2 in, three shut-down days. With these assumptions and the adjustment of duration (2), the day of shut-down was defined. This definition is less constricting than the field practice, which may call for shutting down when the amount of precipitation per day is more than 2 in.

The daily precipitation data for five precipitation gages on the Gifford Pinchot National Forest were compiled from climatological data published by the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce in order to define the number of shut-down days. They were identified by months of the timber-harvesting season from May to October and covered a period of 16 years ranging from 1966 to 1981. With these data and the assumption of a 99.9 percent one-sided confidence interval, Equation 3 was used to estimate the shut-down days for May through October for each precipitation gage. The estimated figures are contained in Table 2. The table indicates that more shut-down days would occur in May and October, whereas in July there is the least chance of shutting down. The number of estimated shut-down days is higher than the average of the last few years and can be considered as the upper limit.

The fourth step of the procedure was to estimate costs considered in the procedure. For this purpose, it was assumed that a logger harvests 1 mmbf (2360 m^3) per month and 2 mmbf (4720 m^3) per season and no more than seven seasons per sale unit and that the shut-down cost is $100/mbf/day (note that the current shut-down cost ranges from $69 to $81/mbf/day). In other words, for five working days per week, the shut-down cost is $5000/day. Further assume that the construction costs per mile for rocked and unrocked roads are, respectively, $145 300 and $99 100 with a difference of $46 200 and that the vehicle operation cost and road maintenance cost of dirt roads are, respectively, 8 percent and 30 percent higher than those of aggregate roads. With additional assumptions of $1.5/mbf/mile of timber-haul cost and $670/mile/season of maintenance cost for aggregate roads, Equation 4 may be modified as shown below (1 mile = 1.6 km; 1 mmbf = 2360 m^3):

$$(145\,000 - 99\,100)M \geq 0.1 \times 1.5 \times 1000 \times M \times V + 0.3 \times 670 \times M + 5000D \quad (5)$$

Table 1. Timber volume and new roads by ranger district.

Ranger District	No. of Projects	Timber Volume (mmbf)	New Roads (miles)
Randle	58	327.40	133.70
Packwood	39	235.20	98.90
St. Helens	42	327.40	84.82
Mt. Adams	32	240.90	145.50
Wind River	26	325.70	124.21
Total	197	1456.60	587.13

Note: 1 mmbf = 2360 m^3; 1 mile = 1.6 km.

Table 2. Estimated shut-down days by district and by months of timber-harvesting season.

Precipitation Gauge	Ranger District	May	June	July	August	September	October
Randle	Randle	4	4	2	3	6	7
Packwood	Packwood	3	3	2	3	4	6
Cougar	St. Helens	6	5	3	4	6	10
Mt. Adams	Mt. Adams	1	2	1	2	3	5
Carson Fish Hatchery[a]	Wind River	3	4	1	4	5	9

[a]Data for 1966 to 1979 were measured at the Wind River precipitation gauge, which is located 4 miles from the Carson Fish Hatchery.

Table 3. Road construction, vehicle operation, road maintenance, and shut-down costs by alternative.

Alternative	No. of Projects	New Roads (miles)	Cost ($) Construction	Vehicle Operation	Road Maintenance	Shut-Down	Total
1. All aggregate roads	197	587.13	85 310 000	7 428 900	360 600	0	93 099 500
2. All dirt roads	197	587.13	58 201 000	7 658 600	468 300	18 740 000	85 067 900
3. Both types							
Aggregate roads	79	122.61	17 815 000	1 826 600	74 200	0	19 715 800
Dirt roads	118	464.52	46 034 000	6 102 500	372 000	8 950 000	61 458 500
Total	197	587.13	63 849 000	7 929 100	446 200	8 950 000	81 174 300

where

M = new roads (miles),
V = timber volume (mmbf), and
D = number of shut-down days.

Equation 5 indicates that when the difference in construction cost between two types of roads is larger than or equal to the sum of shut-down costs and differences in operation and maintenance costs between two roads, the construction of a dirt road is preferred. The equation may be simplified and takes the following form:

$$(46 - 0.05V)M - 5D \geq 0 \quad (6)$$

From the foregoing assumptions, 2 mmbf of timber could be logged within two months. The shut-down days are counted for the two consecutive months that have the least combined shut-down days. For example, as shown in Table 2, the least combined shut-down days per season (five) for the Wind River Ranger District can be in the period from June to July or from July to August. In the Mt. Adams Ranger District, the three shut-down days can be a sum of shut-down days of May and June, June and July, or July and August.

In the last step, by using Equation 6, the conditions given were used to evaluate the 197 projects that had been selected from the analysis in step 2. The results of this evaluation are contained in Table 3 and expressed as the third alternative. The table indicates that it is more economical to build aggregate roads in 79 projects and to construct dirt roads in 118 projects. With consideration of shut-down costs, the third alternative for constructing 122.61 miles (196.1 km) of aggregate roads and 464.52 miles (743.23 km) of dirt roads would cost $81 174 300. Before this analysis was performed, two extreme policy options can be formed. The first option is to build all roads with rock surfacing. The transportation cost for this option is shown as alternative 1 of Table 3; the total cost is $93 099 500. The second option is to consider constructing all new road segments without rock surfacing. This option would cost $85 067 900, which is a sum of shut-down costs along with other associated transportation costs and is shown as the second alternative in Table 3. Comparison of alternatives 1 and 2 indicates that by building unrocked roads, the Gifford Pinchot National Forest can save more than $8 million during a five-year period. The alternative of building all rock-surfaced roads has been the forest's policy for years. However, based on the evaluation procedure developed here, the total transportation cost of alternative 3 is much lower than that of the other two. The savings of alternative 3 over a five-year period could amount to $12 million and to $4 million when compared with alternatives 1 and 2, respectively. A $12 million savings over 5 years or $2.4 million savings per year indicates that an approximately 20 percent transportation cost reduction for the Gifford Pinchot National Forest is possible, even if the forest pays $9 million of the shut-down costs to timber purchasers.

Building unrocked roads is increasingly becoming a major factor for the determination of local road design standards in the Gifford Pinchot National Forest. In the last couple of years the forest has constructed nearly 8 miles of all-weather unrocked roads. In addition to a dozen miles per year on the plan, the actual savings by building lower-standard roads over the time period 1981-1985 are approximately $2 million, which accounts for 4 percent of annual transportation costs in the Gifford Pinchot National Forest.

CONCLUSIONS

The purpose of this paper has been to present the methods for determining the economic feasibility of rock surfacing. Since the capacity of unrocked roads is determined by the physical capability of handling the traffic and the number of shut-down days, the traffic demand and soil conditions, along with the precipitation duration and quantity, were employed to develop an evaluation procedure. The procedure was applied to a five-year timber sale plan of the Gifford Pinchot National Forest. It has been found that using the developed procedure for determining the need for rock surfacing may lead to a savings of 20 percent in local road construction cost. The application demonstrated that such a procedure could be applied to developing regions, particularly where the traffic demand is seasonal and not of long duration.

ACKNOWLEDGMENT

The concept of this study has been used to persuade transportation planners and district rangers in Gifford Pinchot National Forest to shift from the policy of building all rock-surfaced roads to consideration of building all-weather unrocked roads to save 4 percent in transportation costs. The opinions and conclusions expressed in the paper are ours. They are not necessarily those of the Forest Service.

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Simple Overlay Design Method for Gravel Roads

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A simple method to use deflection measurements for design of overlay thickness on low-volume gravel roads is described. Deflection values are recorded at the center of a circular loading plate and at a certain distance from the center. By using the theory of elasticity, it has been found that a certain arithmetic function of the two deflections measured varies almost linearly with the subgrade modulus within rather wide limits of thickness and elastic modulus of the gravel layer; the relation is nearly independent of these values. This relation has been confirmed by analysis of a large number of measurements made by the falling-weight deflectometer on a number of gravel road sections. Similarly, a relation for determination of the upper layer thickness in a two-layer system has been found. Determination of the design deflection meets with two problems: variation along the road and variation with season. The effect of variation along the road will be solved by using running averages and that of seasonal variations by applying a weighting factor. For simplification of the design procedure, it has been assumed that there is a constant ratio between the subgrade modulus and the modulus of the gravel layer; this assumption has been confirmed by actual measurements. Analysis of the standard designs prescribed by the Swedish Road Specifications on different subgrades at different traffic intensities has shown a unique relation between vertical subgrade stress and traffic intensity at each subgrade type. The required equivalent overlay thickness may therefore easily be selected and the corresponding overlay thickness of different paving materials determined. A discussion follows regarding the practical problems associated with the measurement procedure, such as length of intervals between measurements, magnitude of load applied, nonlinearity of materials, and seasonal variations.

The purpose of this study is to present a simple evaluation procedure for the bearing-capacity assessment of gravel roads and an overlay design method.

The study is based on numerical values obtained from the computer program BISAR (1) for the calculation of stresses, strains, and deformation in multilayer systems according to the theory of elasticity. Trends of the deformation behavior have been studied rather than absolute values, in order to avoid the unrealistic results that may emerge from such programs, especially when applied to values from dynamic [falling-weight deflectometer (FWD)] tests.

The study is divided into three main parts:

1. The design method, which is based on the relations obtained from the theory of elasticity and tested against actual measurements performed on sections with known subgrades, gravel thickness, and frost susceptibility;
2. Discussion of the design parameters, i.e., the E-moduli, the allowable stress, and the justification for the use of the stress in the subgrade as design criterion; and
3. Treatment of some practical problems associated with the measurement procedure and summary of the whole method as it would be used in practice.

DESIGN METHOD

The thickness design method had to satisfy two main requirements: first, to comply with the current design practice in Sweden, i.e., with the Swedish Design Specifications [Byggnadstekniska Anvisningar (BYA)] (2); second, to use the two deformation values resulting from deflection measurements at the loading plate center and at a certain distance from that center (e.g., those that use the FWD). Those two deformation values should reflect the bearing capacity of the subgrade and the existing thickness of gravel on top of it. In order to fulfill the first requirement, the standard designs of BYA were analyzed by means of the BISAR program; a load of 50 000 N was assumed to be applied to a plate of 15-cm radius (loading conditions typical for FWD).

The values obtained for the allowable stresses calculated from BYA were plotted against the average traffic flow in every traffic class, and the results are shown in Figure 1. By extrapolation to the traffic flow of 500 vehicles/day, the allowable stresses for each of the subgrade types were obtained for this traffic flow.

In order to find a useful indication of the subgrade bearing capacity, a study has been performed of subgrades that have a variation of bearing capacity from E_u = 15 MPa to E_u = 100 MPa; different moduli of the upper layer are assumed and again each has a thickness variation from 10 to 100 cm. The two surface deformations D_0 and D_x at the plate center and 450 mm from the center corresponding to every subgrade, gravel modulus, and thickness combination were obtained by the aid of the BISAR program. Table 1 represents a typical example from the study.

Many arithmetical combinations of the surface deformation values were studied (not shown in Table 1) and plotted against the E-modulus of the subgrade and the thickness of the upper layer. The expression $V = (1/D_x) - (1/D_0)$ has been found to be a useful indication of the bearing capacity of the subgrade. Figure 2 shows the linear relation $(1/D_x) - (1/D_0)$ against E_u and its relation to the modulus of the upper layer and its thickness. The scatter lines shown correspond to the thickness range of 10-70 cm, which is seldom exceeded in gravel roads.

Figure 3 illustrates the relation between $(1/D_x) - (1/D_0)$ and h. Each group shown belongs to one subgrade modulus, and the variation within