MPC REPORT NO. 93-22

APPRAISAL AND APPLICATION OF MODELS FOR UNPAVED ROADS

Arthur P. Boresi
James T. Palmer

August 1993

APPRAISAL AND APPLICATION

OF

MODELS FOR UNPAVED ROADS

Arthur P. Boresi, P.E., PH.D.
James T. Palmer

University of Wyoming
Department of Civil and Architectural Engineering
Laramie, Wyoming 82071

July 1993

This cooperative study was funded by the U.S. DOT's University Transportation Centers Program through the Mountain Plains Consortium, the Wyoming Transportation Department (WTD) and the University of Wyoming. Special recognition is given to the USDA Forest Service, Medicine Bow District Office, for their cooperation with data collection.

Disclaimer

PREFACE

This report covers the first year of a two-year study of unpaved roads. Maintenance and reconstruction models of unpaved roads are reviewed. These models are based upon empirical and mechanistic methods, and they have the objective of evaluating deterioration, roughness propagation parameters, scraping maintenance, surface material loss, surface material selection and surface thickness. Unfortunately, most models require an extensive data base of road material properties to establish the values of coefficients in the model formulas. The transferability of models from one site to another is questionable. The use of these models in road management decisions is difficult, since they are fairly complex, and require accurate material properties as input.

For these reasons it appears that, at present, sound preventive maintenance practices are a more beneficial way of reducing unpaved road costs. Therefore, a maintenance guidance manual for unpaved roads is presented in Appendix A. The objective of this manual is to provide sound maintenance guidelines for personnel who have maintenance responsibilities. It is intended as a working manual, and as such, is subject to revision and improvement. The authors would appreciate receiving comments and suggestions for improvements.

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY 1

APPRAISAL AND APPLICATION OF MODELS FOR UNPAVED ROADS 5
- Introduction 5
- Deterioration and Maintenance of Unpaved Roads 9
- Definitions and Classification of Unpaved Roads 11
- Control of Deterioration 13
- Adequately Designed Roads 15
- Roads with Weak Surface Layer 15
- Roads with Weak Roadbed Material 16
- Models for Unpaved Road Thickness-Strength Relations 16
- Central Tire Inflation: The USDA - Forest Service Program 20
- Soil Stabilization: Soil/Soil Additive Interaction 21
- Summary and Conclusions 22

SELECTED REFERENCES 25

APPENDIX A 29
- Introduction 31
- Road Classification and Maintenance Requirements 31
- Road Classification 32
- Maintenance Requirements by Road Type 35
- Maintenance Activities and Scheduling 37
- Conclusion 52
- Selected References 53

MANUAL APPENDIX A 55
- Introduction 57
- Stabilization 57
- Compaction 58
- Reaction of Additives 58
- Additives Products 60
- Conclusion 63
- Selected References 65

LIST OF FIGURES

Page

Figures 1a and 1b. Transverse Road View of Corrugations 7
Figures 2a and 2b. Longitudinal Road View of Corrugations 8

APPENDIX A: Maintenance Guidance Manual for Unpaved Roads in the Rocky Mountain Region

Figure 1. Soil Water Bar 41
Figure 2. Rock Water Bar 42
Figure 3. Log Water Bar 43
Figure 4. Rubber Water Bar 44
Figure 5. Log Corduroy 46
Figure 6. Landing Craft Mat Reinforcement 47
Figure 7. Road Cross Section, Crown Slope 48
Figure 8. Shoulder Berm 49

EXECUTIVE SUMMARY

The organization of this executive summary follows that of the main document with each section briefly reviewed.

Introduction

Low volume unpaved roads form a large part of the roadway network. However, in many cases, unpaved roads receive little maintenance attention compared to paved roads. A low volume unpaved road ordinarily is considered to have a design average daily traffic value of 400 vehicles or less. Although they carry relatively few vehicles, many low volume unpaved roads are subject to heavy loads. The deterioration of unpaved roads is manifested by the creation of ruts, corrugations (washboard effect), and potholes. These defects result from the inability of the road/road surface to sustain the traffic loads, with each type of defect related to road surface\subsurface material properties. The deterioration of unpaved roads may be greatly reduced or healed through the use of central tire inflation (CTI) systems that are used in heavy vehicles (timber hauling trucks, etc.) to reduce vehicle tire pressure when traveling over unpaved roads. These CTI systems are appropriate for use in controlled traffic roads (e.g., forest service roads), but requiring their use on uncontrolled traffic roads (e.g., county, state roads) is not practical or cost effective.

Deterioration and Maintenance of Unpaved Roads

Various models have been proposed to estimate the deterioration and maintenance requirements of unpaved roads. These models are based upon both empirical and mechanistic methods, and they also attempt to evaluate mechanisms of deterioration, roughness propagation parameters, scraping maintenance, surface material loss, surface material selection and surface thickness.

Definitions and Classification of Unpaved Roads

Various agencies employ different definitions, classification methods, and deterioration mode descriptions.

Definitions

Generally, unpaved roads may be defined as Engineered Roads and Tracks.

Engineered Roads

Engineered roads have controlled alignment, width, and cross-section profile and drainage.

Tracks

Tracks are roads that are formed by traffic along natural contours, with removal of top soil, and without removal of top soil.

Classification

Unpaved roads may be classified as gravel (sand, gravel or crushed rock) roads, or earth roads. Earth roads include tracks, unpaved roads with surface material that does not meet gravel road specifications, and unpaved roads with surface of predominantly fine soil materials.

Deterioration

The fundamental causes of deterioration are wear and abrasion of road surface due to traffic loads, and deformation of the road surface by traffic, water and wind. These modes are affected differently under dry and wet weather conditions.

Models for Unpaved Road Thickness-Strength Relations

These models are based upon empirical-statistical-mechanistic concepts. They relate required road surface thickness to road material strength for various design loads, allowable rut depth and tire inflation pressures. Often, these models require an extensive data base of road material properties to establish the values of coefficients in the formulas. The transferability of the models from one site to another is another question that must be addressed. In addition, the efficient use of these formulas in actual road management decisions is debatable, since they are fairly complex and, as noted, require accurate material properties as input.

Central Tire Inflation: The USDA-Forest Service Program

The Central Tire Inflation (CTI) program sponsored by the USDA-FS has considerable merit. The CTI technology allows the driver to change tire pressure while the vehicle is in motion, to match road surface properties, with the objective of reducing road damage. Indications are that CTI is a viable cost effective method of reducing (and even curing) road damage, particularly for unpaved forest service roads subjected to heavy truck loads (e.g., timber hauling logging trucks or mining haul trucks).

Soil Stabilization: Soil/Soil Additive Interaction

Common uses of soil additives limit road dust and, in part, strengthen the road surface. These additives are applied to road surfaces in a prescribed manner, usually from 0.50-1.00 gal per square yard of road surface. However, few studies attempt to measure soil properties and match them to additive properties to achieve prescribed road surface specifications.

In the second year of the present study, the interaction of soil and soil additives will be studied, with the objective of matching soil and soil additive properties to achieve a road surface of high performance qualities. A list of candidate additives is given in Appendix A.

Summary and Conclusions

Current models of unpaved roads are based upon statistical analyses of experimental data, guided by or preceded by mechanistic analyses. The complexity of these models and their questionable transferability to new databases mitigates against their wide acceptability as a design tool.

The use of CTI systems appears to be a very effective method of damage control of forest timber haul roads. However, the use of CTI systems on all vehicles that travel on county and state unpaved roads is not feasible. In addition, the use of CTI systems does not address the question of improving methods of road maintenance and reconstruction to increase road life.

The second phase of the present study will investigate soil/soil additive combinations for optimum road performance.

A maintenance guidance manual for unpaved roads in the Rocky Mountain region is presented in Appendix A. The objective of this manual is to provide maintenance guidelines for personnel who have road maintenance responsibilities. It is intended to be a working manual. As such, it is subject to revision and improvement. The authors would appreciate receiving comments and suggestions for improvements from users.

APPRAISAL AND APPLICATION OF MODELS FOR UNPAVED ROADS

Introduction

In the United States, the major portion of research on road roughness has been directed toward paved asphalt/concrete roads. These studies have taken two distinct approaches. One approach starts with empirical methods followed by enhancements based upon mechanistic principles (Paterson, 1987; World Bank, 1987). It uses comprehensive field data from in-service roads and statistical techniques to evaluate models that are based upon mechanistic principles. A second approach employs a mechanistic model, directly calibrated empirically with field data, to evaluate damage produced by traffic to be used as input to the major United States study on highway cost allocation (Rauhut, Lytton and Darter, 1984).

Unlike paved roads, the roughness of unpaved roads is best studied and modelled by empirical methods based upon the field performance of a variety of roads to identify and quantify the factors involved. The deterioration of unpaved roads is strongly affected by the behavior of the surfacing material under the actions of traffic and environment (Robinson, 1980; Heath and Robinson, 1980; Visser, 1981; Paterson, 1987, 1991).

Recently the role of vehicle tire structure and pressure have been shown to have a strong influence on unpaved road deterioration (Hodges and Della-Moretta, U.S.D.A. Forest Service Publication in preparation), particularly with regard to the tendency of unpaved roads to corrugate (washboard). However, the proneness of unpaved roads to corrugate is still not clearly understood. Research by the U.S. Forest Service on Central Tire Inflation vehicles has shown that low inflation pressures reduce or eliminate corrugating (Stuart, Gilliard, and Della-Moretta, 1987a), and in certain situations remove (heal) the corrugations.

Various forms of road roughness occur in paved and unpaved roads. For example, ruts and corrugations (washboard effect) are two common forms of road roughness. Road roughness is a characteristic of the longitudinal profile of a road surface. However, a significant measure of road roughness must include the effects of road surface profile, characteristics of the vehicles that travel over the road, and sensitivity of the vehicle occupants. Surface deviations (roughness amplitude and wave length) usually tend to be random in nature. They are often characterized by amplitudes and wave lengths of various magnitudes. The spectrum of amplitudes and wave lengths may be quite complex and cover a broad range of values. For unpaved rural roads, roughness wave lengths are fairly short (washboarding; see Figures 1 and 2), whereas for paved asphalt/concrete roads, the wave lengths are long. A range of wave lengths that excludes the extremely small amplitude and short wave lengths of surface texture and the very long wave lengths of the longitudinal gradient is 0.1 to 100 m, with 1 to 100 mm amplitudes. Road roughness increases with increasing amplitude and decreasing wave length in this range.

For a given road, the road roughness spectrum can be represented by a power spectral density (PSD) function that expresses mean square amplitude as a function of wavelength (or wave number - the inverse of wave length). Alternatively, PSD functions may be expressed as slope (derivative of amplitude) or acceleration (derivative of slope). Each PSD function (amplitude, slope and acceleration) has a different effect relative to road maintenance, user comfort and vehicle wear; for example, the acceleration PSD relates significantly to vehicle vibrations and occupant comfort (Sayers, Gillespie and Queiroz, 1986). The relative significance of the various PSD functions on road economy, vehicle response and occupant comfort complicates the establishment of a relevant roughness statistic.

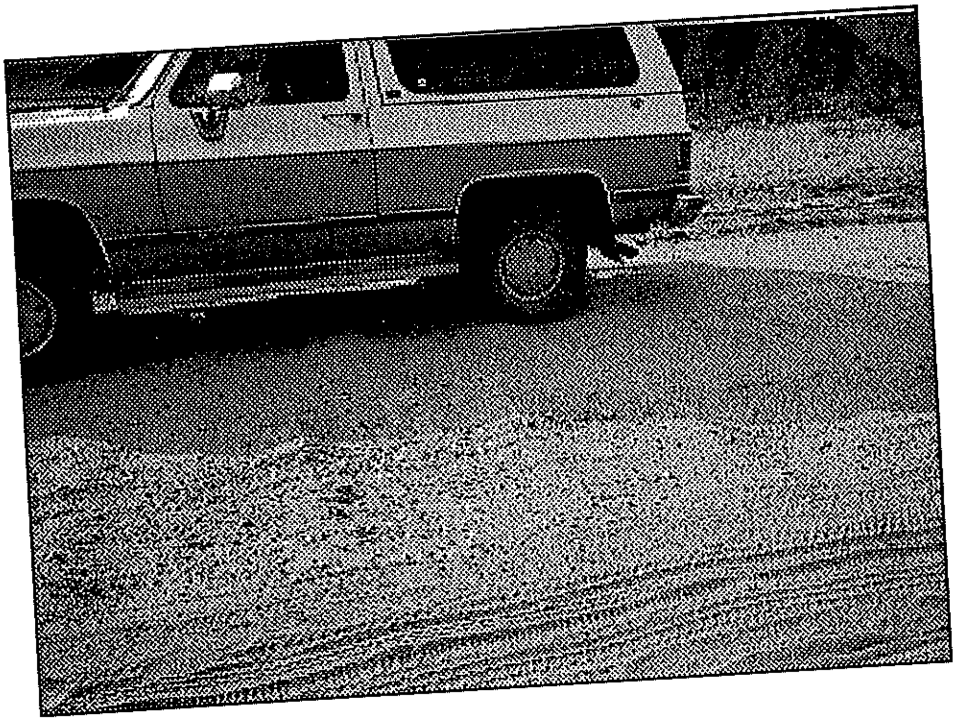

FIGURE 1a. Transverse Road View of Corrugations
Note motorcycle tracks at road edge due to cyclists' attempts to avoid corrugations.

FIGURE 1b. Transverse Road View of Corrugations
Longitudinal wave length corresponds approximately to footprint of 16-inch diameter tires.

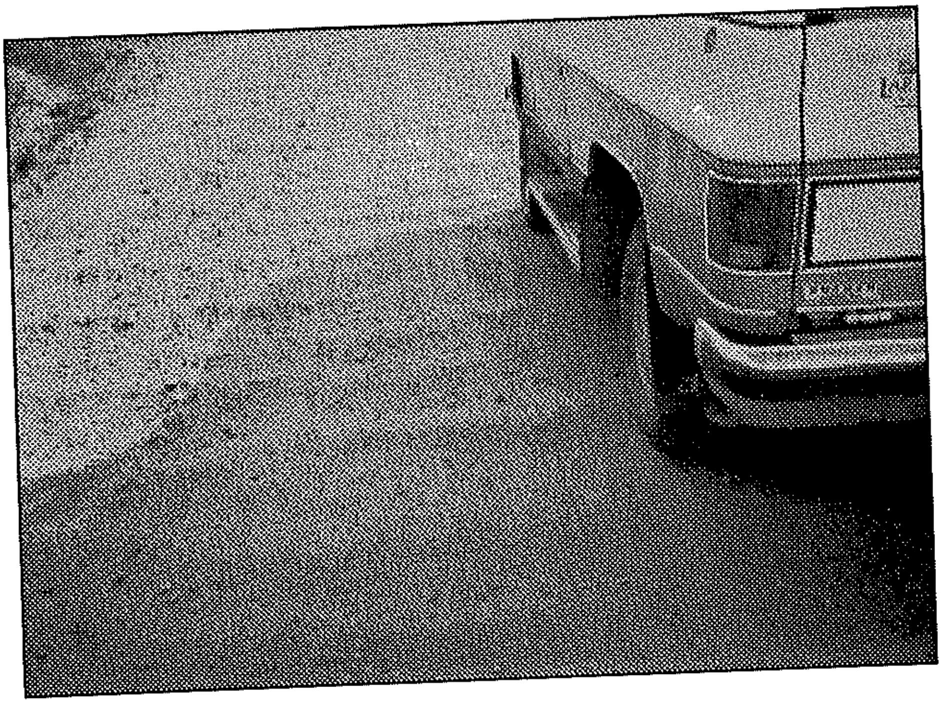

FIGURE 2a. Longitudinal Road View of Corrugations

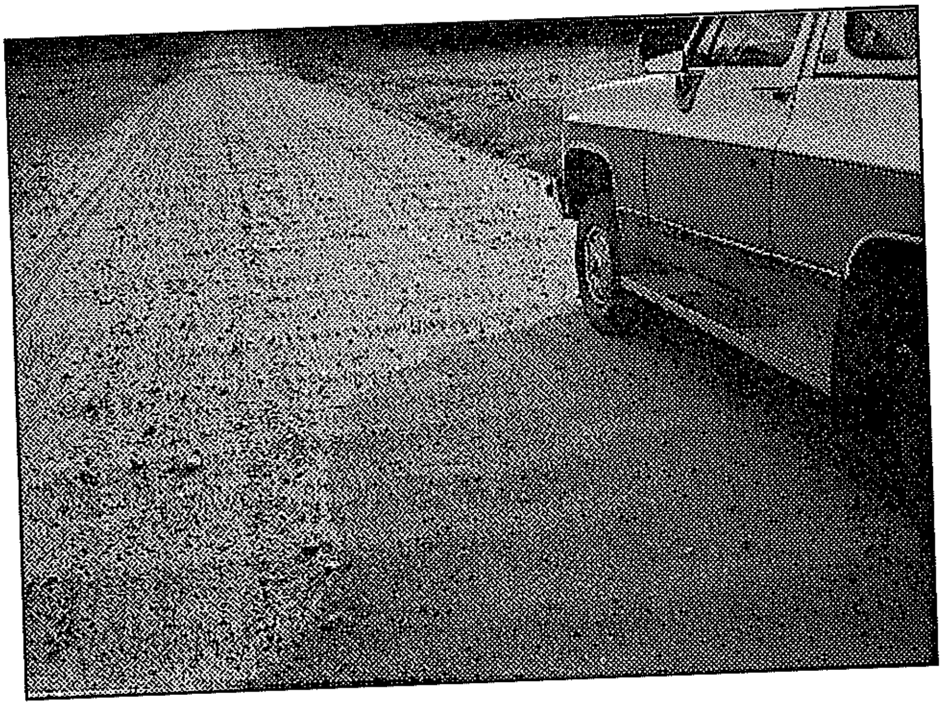

FIGURE 2b. Longitudinal Road View of Corrugations

Unpaved roads have broad spectra of roughness, that is, an appreciable content in all wave bands, but with noticeably more roughness in the short wave lengths than do paved roads. Gravel roads have spectra somewhat similar to surface-treated paved roads; whereas, earth road surfaces show greatest roughness in the short wave length range (less than 1 m), since fine-grained materials tend to develop small depressions (washboard effect), humps and potholes (Sabers, Gillespie and Queiroz, 1986).

The response of a moving vehicle to road roughness depends on the mechanical properties (spring/stiffness) of the vehicle, vehicle speed and road roughness (Gillespie, Sabers and Segel, 1980). The effect of roughness amplitude is transmitted mainly into a vertical impulse to the vehicle wheels. The wave length (wave number) of the roughness profile transforms into a frequency pulse (cycles per sec, Hz) dependent on vehicle speed. Thus, the amplitude and the frequency of the road corrugations produces a vehicle response dependent upon the dynamic characteristics of the vehicle and tire pressure. Stuart, et al., (1987a) have found that damage to native- and aggregate-surface roads is significantly decreased when tire pressures are lowered. They also found that the impact on trucks, cargo and occupants are significantly reduced when low-pressure tires are used, resulting in lower truck maintenance and repair costs. Lower tire pressures also seem to result in fewer medical claims due to occupant injuries.

Deterioration and Maintenance of Unpaved Roads

A World Bank study (1987) estimated that a third of the unpaved roads outside urban areas in developing countries are in need of restructuring. This estimate is probably applicable to unpaved roads in developed countries, as well. However, a similar study of unpaved roads in developed countries has not been made.

Increased efforts are needed to develop and implement improved road management and planning tools for maintenance of unpaved roads (comparable to those used for paved roads). In particular, such tools are required for the allocation of financial resources, for estimating timing and financial needs of road maintenance and reconstruction programs. Tools are also needed for evaluation of costs or road use, for purposes of allocation of costs to users through taxation or direct charges. Finally, determination of when unpaved roads should be upgraded (for example, paved) is an economical question, as well as a technical question (see When to Pave a Gravel Road, Document No. PA-76, distributed by The Wyoming Technology Transfer Center, University of Wyoming, Laramie, WY 82071).

Much of modern pavement design is based upon theoretical analyses of elasticity, plasticity, and soil mechanics, including shear strength, behavior of materials under traffic loads, and multilayer structural analysis. However, these methods have always been qualified by empirical results in the formulation of practical criteria of road design, since the long term complex behavior of roads and indexes of deterioration (e. g., riding quality, passage criteria, etc.) include subjective considerations. Unfortunately, the very complexity of the problem and the large number of variables involved has led to a greater dependency upon mechanistic analyses to extrapolate the design to include new load limits and materials. In other words, a combination of approaches, mechanistic and empirical, is required. Recent studies reflect this approach. In particular, the definitive work of Paterson (1987) uses an empirical approach that employs field data and statistical methods to evaluate models, these models being guided by mechanistic concepts. In contrast, the approach taken by Rauhut, et al. (1984) is one in which a mechanics model is developed and then calibrated to fit field data. These methods have been applied to study the deterioration and maintenance of unpaved roads, including mechanisms of deterioration, models for roughness propagation, scraping maintenance, surface material loss, selection of surface material and determination of surface thickness (see Chapter 3, Paterson 1987).

Definitions and Classification of Unpaved Roads

I. Definitions (as used by Paterson, 1987)

(a) Engineered Roads: These are roads that have controlled

(i) alignment,

(ii) formation width,

(iii) cross-section profile and drainage.

(b) Tracks: These are roads that are formed by trafficking along natural contours,

(i) with removal of top soil,

(ii) without removal of top soil.

Unpaved roads that are classified as part of a country's network are either engineered or partly engineered. Tracks are not usually classified. Studies of the effects of deterioration and maintenance have been mainly on engineered unpaved roads, because available data bases deal only with such roads and do not ordinarily include tracks.

II. Classification of Unpaved Roads (as used by Paterson, 1987)

(a) Gravel Roads: These roads, as used here, include sand and gravel or crushed stone.

(b) Earth Roads: This terminology is sometimes used

(i) to denote a track as opposed to an engineered road,

(ii) to denote all unpaved engineered roads, with surface material that does not meet the material gradation specifications for gravel of the responsible agency. For example, see the Kenya study and the Kenya Ministry of Works specifications (Hodges, Rolt, and Jones 1975),

(iii) to specify unpaved roads that have a surface of predominantly fine soil materials with more than 35 percent finer than 0.075 mm particle size (Brazil study, GEIPOT 1982). This definition has also been used by Paterson (1987).

III. Deterioration of Unpaved Roads

Deterioration modes may be classified as follows (Paterson 1987):

(a) Fundamental Mechanisms (Modes) of Deterioration

(i) Wear and abrasion of the surface under traffic loads,

(ii) Deformation of the road surface by traffic, water, and wind.

These modes of deterioration are affected differently under dry and wet weather conditions. Under dry weather conditions, deterioration is due principally to roughness and material loss. Under wet weather conditions, deterioration is related primarily to the strength of the road surface and road bed material. The approach to modelling of deterioration of unpaved roads has been categorized under four main groups (Visser 1981); namely, (1) dry weather deterioration, (2) wet weather deterioration, (3) wet weather deterioration with weak road-surface layer, and (4) wet weather deterioration with weak road-bed material.

(b) Dry Weather Deterioration of Unpaved Roads

For dry weather deterioration of unpaved roads, the principal mechanisms are

(i) Wear and abrasion of the surface, resulting in the production of loose materials, ruts, and potholes,

(ii) Loss of surface material by scattering (whip-off) and dust,

(iii) The pile up of loose materials by traffic into corrugations (washboard effect),

(iv) Ravelling of the surface as a result of insufficient cohesion of the surface material to remain intact. Ravelling may be due to either the abrasive action of vehicle tires or improper blading of the surface. In areas where travelling occurs, vehicle traffic (tire action) continues the abrasive action. The loose material is removed from the abraded area, resulting in depressions and further roughness.

These principal mechanisms produce roughness and resulting material loss. Roughness and material loss are difficult to predict analytically. Therefore, they are best studied and modelled by empirical methods. These methods require data from the field performance of a sufficient variety of roads to identify and quantify the factors involved.

Control of Deterioration

Current literature does not contain rigorous guidelines to control deterioration. However, there is a general consensus that certain properties of the surface material are necessary to control ravelling, looseness of the top surface, and corrugating (Robinson 1980, Heath and Robinson 1980, Visser 1981). In particular, a minimum level of fines appears to be a primary factor for prevention of ravelling, looseness, and corrugating.

For example, Visser (1981) recommends that the percentage of material finer than 0.075 mm be kept greater than 14; that is

$$P075 \geq 14 \text{ percent} \qquad (1)$$

where P075 is the percentage of material finer than 0.075 mm, and 14 percent is based upon Visser's review of empirical studies. This recommendation is consistent with the findings of other investigations. However, other factors also enter. For example, in addition to a minimum material fines content, the angularity and gradation of material particles appear to play a role in suppressing the formulation of corrugations. This fact is probably a result of an increase in shear stress of the material due to correct angularity and gradation (Heath and Robinson 1980).

According to many researches (Heath and Robinson 1980), corrugations are formed, propagated, and perpetuated by forced oscillations at the resonant frequencies of vehicle suspension and tire systems. However, other researches (Paterson 1987, Della-Moretta 1992) have indicated that corrugation frequencies are related more closely to tire resonant frequencies.[1] Indeed, research by the U. S. Forest Service on Central Tire Inflation (CTI) vehicles has shown that low tire pressure reduces or eliminates corrugations; that is, cures existing corrugations (Stuart et al. 1987a; Taylor 1987; Ashmore and Sirois 1987). These findings support the importance of tire resonance and surface-roadbed shear strength.

(c) Wet Weather Deterioration of Unpaved Roads

The study of wet weather deterioration of unpaved roads may be subdivided into studies of roads that

- (i) are adequately designed and built. Such roads are defined as a properly configured combination of compacted roadbed and layers of surface material to carry the designated traffic.
- (ii) have a weak surface layer.
- (iii) have a weak roadbed.

---

[1]An increase in corrugation of unpaved roads in certain areas of the Medicine Bow Forest road system has also been linked to the change in automobile suspension systems from leaf springs to coil springs; comment by Gary Moats, USDA Forest Service office, Laramie, WY.

Adequately Designed Roads

For adequately designed roads under wet weather conditions, the pattern of deterioration is controlled mainly by the shear strength of the surface/roadbed materials. If the shear strengths of the surface and roadbed materials are adequate for the traffic loads, deterioration occurs mainly at the surface. The usual modes of deterioration under these conditions are (1) surface erosion due to effects of environment, (2) wear and abrasion of the surface layer by traffic, resulting in rutting and loss of surface material, and (3) formation of potholes in the surface layer. Potholes are generally formed in depressions in the surface due to imperfect construction or to traffic wear. Rain water or water due to snow melt on the surface accumulates in depressions. When a vehicle wheel rolls over the water filled depression, the water is stirred up and pressurized by the wheel. As a result fine material is absorbed and suspended in the water. With continued traffic, water with the suspended fines is forced out of the depression and a pothole is started. Once started, the pothole grows rather rapidly under the presence of water and additional traffic. Freezing and thawing during winter months also accelerates the process of pothole formation.

Roads with Weak Surface Layer

If the surface layer has inadequate shear strength, shear failure and excessive deformation occurs. Hence, under wet conditions, the road surface becomes soft and slushy. The road may be able to support the passage of a few light vehicles, but with increased traffic and heavier vehicles the road will become impassable.

Usually, a simple shear test, such as the California Bearing Ratio (CBR), is used to measure shear strength. However, other measures such as the plasticity index and the percentage of fines also may be related to shear strength. Empirical formulas have been developed (Visser 1981) relating the soaked CBR of the surface material to ensured vehicle passage in the form

$$SFCBR \geq 8.25 + 3.75 \log_{10}(ADT) \qquad (2)$$

where: SFCBR = the soaked California Bearing Ratio at standard Proctor laboratory compaction (600 kJ/m^3), in percent. Equation (2) gives the minimum SFCBR for ensured vehicle passage.

ADT = the Average Daily Traffic in both directions (Vehicles/day).

Roads with Weak Roadbed Material

When the in situ roadbed soil is weak, a road surface is required to protect the roadbed and to limit deformation to acceptable levels. If the road surface is also weak, the subgrade (roadbed) is often over stressed. Then rutting, or permanent deformation, occurs in the wheel paths. This type of failure is common in areas of poor surface and subsurface drainage, particularly during spring conditions in cold climates or in areas of weak soil where design standards cannot be met. In such cases, the thickness and the stiffness of the surface layer must be sufficiently large to distribute traffic loads, and to keep stress and strain in the roadbed at sufficiently low levels, so that excessive permanent deformation of the roadbed is prevented. These stress and strain levels strongly depend on the volume and load magnitude of traffic. They also depend on the shear strength of the in situ roadbed material, which in turn, depends upon moisture content.

Models for Unpaved Road Thickness-Strength Relations

The United States Corps of Engineers has developed empirical based formulas for required thickness and material strength. The criteria developed have been characterized by the following simplified model (equation) that relates the thickness of the gravel surface to surface and roadbed soil properties (Hammitt 1970; Barber, et al., 1978; see particularly, Paterson 1987)

$$\log_{10}HG = 1.40 + 12.3C_1^{-0.466}C_2^{-0.142}NE^{0.124}RD^{-0.5} \quad (3)$$

where:
- HG = the thickness of the gravel surface, mm
- C_1 = soaked CBR of surface material, percent
- C_2 = soaked CBR of roadbed soil, percent
- NE = design number of cumulative equivalent 49 kN (9000 lbs) single wheel loads at 550 kPa (80 psi) tire pressure
- RD = maximum allowable mean rut depth, mm

For other single wheel loads (kN) and tire inflation pressures (kPa), the coefficient 12.3 in Eq. (3) is replaced by the quantity

$$0.856\ P^{0.235}\ Q^{0.285} \quad (4)$$

where:
- P = the equivalent single wheel load (kN)
- Q = the tire inflation pressure (kPa)

and NE in Eq. (3) is replaced by N, the number of combined loads with values (P, Q).

For data on roads in Thailand and Ecuador, Greenstein and Livneh (1981) have given an estimate of material strength required of earth roads, for a maximum rut depth of 75 mm, as

$$C_2 = 0.0138\ N^{0.172}\ P^{0.580}\ Q^{0.490} \quad (5)$$

Equations (3), (4) and (5) indicate a very strong influence of tire pressure. In particular, Greenstein and Livneh (1981) estimate that for their data

$$N \sim Q^k \quad (6)$$

Visser (1981) has presented a theoretical mechanistic approach, in which strain induced in the road subgrade are computed. An elastic layered model of the road surface is used to determine the strains. These strains are correlated with respect to resilient modulus and deformation properties of the subgrade. This theoretical approach has been shown to be suitable for special purpose, such as the design of unpaved roads for short-term studies.

However, for more general cases of long-term behavior, the empirical approach has been preferred.

More recently, Copstead (1991) used models based on the Region 6 Surfacing Thickness Program (STP) and the accompanying surface thickness design guide (ARE, Inc. 1990) to predict certain effects of tire pressures on unpaved roads. Copstead arrives at the thickness model in the form of a regression equation

$$RD = 0.1741 \frac{P_k^{.4704}\, t_p^{.5695}\, R^{.2476}}{(\log t)^{2.002}\, C_1^{.9335}\, C_2^{.2848}} \tag{7}$$

where:

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

If Eq. (7) is solved for the repetitions R, the ratio of repetitions R_{STD} of the standard axle to repetitions R_{ACTUAL} of the actual axle may be formed. This ratio is called the equivalent factor (EF) of an axle in terms of the axle load, type of axle, and the tire pressure for the axle. Thus, with Eq. (7), we find

$$EF_{axle} = \frac{R_{STD}}{R_{ACTUAL}} = \left(\frac{P_{k\,ACTUAL}}{P_{k\,STD}}\right)^{\frac{.4704}{.2476}} \left(\frac{t_{p\,ACTUAL}}{t_{p\,STD}}\right)^{\frac{.5695}{.2476}} \tag{8}$$

The Corp of Engineers (ARE, Inc., 1990) used the following relation to calculate P_k

$$P_k = \varepsilon P \tag{9}$$

where ε is the portion of axle load effect on road performance attributable to an equivalent single wheel load (ESWL) and P is the axle load in kips. Typical values of ε that are used in the surfacing thickness and design guide are 0.29 for tandem axles with dual wheels, 0.48 for single axles with dual wheels, and 0.57 for single axles with single wheels (ARE, Inc. 1990). Substitution of Eq. (9) and the values for the standard axle into Eq. (8) yield the result

$$EF_{AXLE} = \frac{(\epsilon P)^{1.8998}\ (t^{P})^{2.3001}}{1{,}433{,}792} \qquad (10)$$

Since the total EF for a vehicle pass or round trip is the sum of the EF's for each axle that passes over a point on the road

$$EF_{TOTAL} = \frac{\sum_{i=1}^{n} [(\epsilon_i P_i)^{1.2998}\ (t_{P_i})^{2.3001}]}{1{,}433{,}792} \qquad (11)$$

For a log truck that can vary its tire pressure, EF_{TOTAL} is the sum of the EF's for the steer, drive, and trailer axles in both the loaded and the unloaded state. The repetitions R is then the number of round trips of the log truck on the road. The number of repetitions of a vehicle operation times the EF for that operation is equivalent (in terms of the effect on the road) to the number of repetitions of the equivalent standard axle load (ESAL) for the operation. Therefore, by Eq. (8),

$$\text{ESALS} = R_{STD} = (R_{ACTUAL})(EF_{TOTAL}) \qquad (12)$$

Then by Eqs.(6) and (12), the minimum thickness t of an aggregate surface layer is

$$\log t = [\frac{5.823(R_{ACTUAL}\ EF_{TOTAL})^{.2476}}{RD\ C_1^{.9335} C_2^{.2848}}]^{.4995} \tag{13}$$

This model needs to be tested for an actual site, since the constants in Eq.(13) (5.823, etc.) depend on statistical analyses of experimental data. This statement also applies to the modeling described by Eqs. (2)-(11).

Central Tire Inflation: The USDA - Forest Service Program

The United States Department of Agriculture (USDA) Forest Service has been investigating the feasibility of using Central Tire Inflation (CTI) technology since 1983. The CTI technology is an air pressure system, installed on a vehicle (usually a timber hauling truck), that allows the driver to change tire pressure to match the road surface properties. The objective of CTI is to adjust tire pressure, while the vehicle is in motion, to adapt the pressure for any given vehicle load, speed and road condition to achieve minimum road damage. The USDA Forest Service manages approximately 360,000 miles of roads. Seventy-five percent of these roads are low volume, single-lane, gravel roads (i.e., unpaved roads). Hence, the Forest Service objective is to reduce the thickness of top road surfaces of these unpaved roads (and hence, costs) necessary to support traffic loads with minimum road damage. The Forest Service has estimated that the use of the CTI system will result in a savings of twenty million dollars ($20,000,000) annually in maintenance and reconstruction costs. Consequently, the Forest Service plans to implement CTI applications in the management of forest roads as soon as possible. The hope is that considerable savings can be realized through CTI, not only in the construction and maintenance of roads, but also in the reduction of truck (vehicle) maintenance and tire wear, and in the extension of haul seasons (Grau and Della-Moretta, 1991; Powell and Brunette, 1991; Simonson, 1991; Greenfield and Cohn, 1991).

Also, a comparison study of the beneficial effects on sedimentation of reduced tire pressure versus normal tire pressure has been conducted by Foltz and Burroughs (1991). Another comparison study by Watkins (1991) illustrated that constant reduced tire pressure may also be beneficial, without the use of CTI systems. In other words, reduced tire pressures seem to be beneficial regardless of the method of achieving reduced pressures.

CTI systems have considerable merit in forest operations, where the major vehicle traffic consists of timber haul trucks. Consequently, in the future, it appears likely that preference will be given to timber harvest bidders who equip their trucks with CTI systems.

Although it may be feasible for the Forest Service to advocate the use of CTI systems on timber haul trucks, it is not practical to require CTI systems on vehicles (passenger cars, motor homes, pickup trucks, grain trucks, truck-trailers, farm vehicles, etc.) that travel on county and state unpaved rural or recreational area roads. Hence, the use of CTI systems has the greatest cost-saving potential in a controlled vehicular traffic area such as that on forest timber roads.

Soil Stabilization: Soil/Soil Additive Interaction

The use of soil additives (magnesium chloride, calcium chloride, lime, etc.) for dust control and partial soil stabilization is common for unpaved road maintenance and reconstruction. Additives are applied on unpaved roads in a prescribed manner, in the usual proportions of 0.50-1.00 gal per square yard of road surface, somewhat independent of the road surface properties. However, there have been very few studies that attempt to accurately match the road soil properties to additive properties, to achieve a road surface that meets prescribed specifications.

In the second phase of the present Mountain Plains Consortium project, the interaction of soil and soil additives will be studied. The objective of this study will be to determine a match between soil and soil additive in order to achieve a road surface with prescribed properties. In cooperation with the USDA Forest Service Laramie, WY regional office, a study of the effects of additives on reconditioning approximately 29 miles of unpaved forest service roads in the Medicine Bow National Forest, west of Laramie, will be performed. Soil samples of the road surface and road sub-surface will be taken before application of additives, and tests will be performed to characterize the road soil properties. After application of additives and a certain time for "seasoning" of the soil/additive mixtures, additional soil samples will be taken and tested, to characterize the properties of the soil/additive mixtures, with the objective of evaluating the effect of additives.

A comparison program of laboratory tests of soils and soil additives will also be conducted. The objectives of the laboratory test program are to develop a method of characterizing the effects of various soil/soil additive interactions, and to establish a correlation between desired road surface properties and the soil/soil additive properties. Various soils from locations throughout the state of Wyoming will be tested. A list of additives that may be tested is given in Appendix A.

Summary and Conclusions

Several models for unpaved roads have been developed (Paterson, 1987, 1991). These models are based upon statistical analyses of experimental data, guided by mechanistic concepts. These models are intended to be used to predict either minimum, maximum and average roughness (as functions of traffic volume, road gradient and curvature, physical properties, rainfall and interval between blading) or the rate of surface (gravel) loss as a function of the same variables. As noted earlier, these models are based upon the analyses of extensive data collected mainly in Brazil (Paterson, 1987, 1991). Comparisons with data from several countries, namely, Africa and North and South America, seem to indicate transferability of the models. However, these kinds of studies and models do not address directly the question of improvement of road maintenance and reconstruction techniques to ensure prolonged road life. Also, extensive testing to ensure transferability is apparently required.

The use of CTI systems is essentially a mechanical means of controlling tire pressure to reduce the damaging effects of heavy loads on weak road surfaces. It appears to be a very effective method of damage control of forest timber haul roads (Greenfield, 1991). However, it too does not address the question of improving methods of road maintenance and reconstruction to increase road life.

There have been few, if any, studies that attempt to characterize properties, either of roadbed soils or mixtures of roadbed soils and soil additives. In particular, there have been no studies that attempt to predict the properties of a soil/soil additive mixture, with the objective of achieving a road surface of prescribed properties.

The second phase of the present study will address the issue of predictability of properties that result from various soil/soil mixtures, with the objective of achieving a road surface with prescribed properties.

SELECTED REFERENCES

ARE, Inc. *Aggregate Surfacing Design Guide.* Pacific Northwest Region of the USDA FS. REP NO. J 669, p.146. 1990.

Ashmore and Sirois. "Influences of the Central Tire Inflation System on Log Truck Performance and Road Surfaces." American Society of Agricultural Engineers: Baltimore, MD, 1987.

Barber, V.L., Odom, E.C., and Patrick, R.W. *The Deterioration and Reliability of Pavements.* Technical Report S-778-8, U.S. Army Corps of Engineers , Waterways Experiment Station, Vicksburg, MS, 1978.

Copstead, R. *Using The Region 6 Surfacing Thickness Program to Predict Some Effects of Tire Pressures on Roads.* San Dimas Technology and Development Center Pacific Northwest Research Station, March 1991.

Della-Moretta, L.B. "Advances in Soil Dynamics." American Society of Agriculture Engineers, Monograph Series, 1992.

Della-Moretta, L.B. "Advances in Soil Dynamics, Traction Section: Traction and Soil Compaction Volume." Paper in progress. ASAE Monograph Series.

Foltz, R. B. and Burroughs, E. R., Jr. "A Test of Normal Tire Pressure and Reduced Tire Pressure on Forest Roads: Sedimentation Effects." In *Proceedings, Forestry and Environment...* Engineering Solutions. ASAE, New Orleans, LA, 1991.

Grau, R. W. and Della-Moretta, L. *Effects of Variable Tire Pressure on Road Surfacings.* Transportation Research Record No. 1291, Vol. 2, p.313. Washington, DC, 1991.

Geipot. *Research on the Interrelationships between Costs of Highway Construction, Maintenance, and Utilization (PICR).* Final Report, 12 volumes. Ministry of Transport, Brasilia, 1982.

Gillespie, T.D., Sayers, M.W., and Segel, L. *Calibration of Response-Type Road Roughness Measuring Systems.* National Cooperative Highway Research Program Report 228. Transportation Research Board, Washington, DC, 1980.

Greenfield, P. H. and Cohn, A. E. *Effects of Variable Tire Pressure on Tire Life.* Transportation Research Record, No. 1291, Vol. 2, p. 346. Washington, DC, 1991.

Greenstein, J., and Livneh, M. *Pavement Design of Unsurfaced Roads.* Transportation Research Record 827, pp. 21-26. Transportation Research Board, Washington, DC, 1981.

Hammitt, G.M. *Thickness Requirements for Unsurfaced Roads and Airfields.* Tech Rep S-70-5. Waterways Experimental Station, Vicksburg, VA, 1970.

Heath, W., and Robinson R. *Review of Published Research into the Formulation of Corrugations on Unpaved Roads.* Supplementary Report 610, p. 21. Transport and Road Research Laboratory, Crowthorne, England, 1980.

Hodges, H.C., Della-Moretta, L.B. *Off-Highway Tire/Road Damage and Healing Mechanisms.* Project Record 8371 1202. Forest Service Equipment Development Center, San Dimas, CA, 1983.

Hodges, J.W., Rolt, J., and Jones, T.E. *The Kenya Road Transport Cost Study: Research on Road Deterioration.* Laboratory Report 673. Transport and Road Research Laboratory, Crowthorne, England, 1975.

Kentucky Transportation Center. *When to Pave a Gravel Road.* Transportation Information Program, Laramie, WY, 1988.

Paterson, W. D. O. *Road Deterioration and Maintenance Effects—Models for Planning and Management.* Baltimore, MD: The Johns Hopkins University Press, 1987.

Paterson, W. D. O. *Deterioration and Maintenance of Unpaved Roads: Models of Roughness and Material Loss.* Transportation Research Record, No. 1291, Vol. 2, p. 143. 1991.

Powell, B. and Brunette, B. *Reduced Tire Inflation Pressure—A Solution for Marginal-Quality Road Construction in Southeast Alaska.* Transportation Research Record, No. 1291, Vol. 2, p. 329. 1991.

Rauhut, J.B., Lytton R.L., and Darter, M.I. *Pavement Damage Functions for Cost Allocation.* 4 volumes. Report FHWA-RD-84/017-020. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 1984.

Robinson, R. "A Survey of Recent Research on Maintenance Criteria and the Deterioration of Unpaved Roads in Developing Countries." *PTRC Summer Annual Meeting,* p. 23. Planning and Transport Research and Computation Company Limited, London, England, 1980.

Sayers, M., Gillespie, T.D., and Queiroz, C.A.V. *The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements.* Technical Paper 45. World Bank, Washington, DC, 1986.

Simonson, R. *Effects of Tire Deflection on Rear-Axle Torque.* Transportation Research Record, No. 1291, Vol. 2, p. 333. 1991.

Stuart E. III, Gilliard, E., Della-Moretta L. "The Use of Central Tire Inflation Systems on Low-Volume Roads." *Fourth International Conference on Low-Volume Roads.* Transportation Research Board, Washington, DC, 1987a.

Stuart, W. H., McCullough, F. B., Carmichael, F. R. III. *Surface Design and Rehabilitation Guidelines for Low-Volume Roads.* Federal Highway Administration No. FHWA/TS-871225. US Department of Transportation, Washington, DC, 1987b .

Taylor, D. J. *National Central Tire Inflation Program—Bose National Forest Field Operational Tests.* Report 8771 1201. Forest Service-USDA, Equipment Development Center, San Dimas, CA, 1987.

Visser, A.T. "An Evaluation of Unpaved Road Performance and Maintenance." Ph.D. dissertation, Department of Civil Engineering, University of Texas at Austin, 1981.

Watkins, G. *Truck Operation at Constant Reduced Tire Pressure.* Transportation Research Record, No. 1291, Vol. 2, p. 342. 1991.

World Bank. *Road Deterioration in Developing Countries.* Policy Paper. Washington, DC, 1987.

APPENDIX A

Maintenance Guidance Manual

for

Unpaved Roads in the Rocky Mountain Region

Introduction

In the United States approximately 65 percent of the roads are unpaved (Eaton, et al., 1988). The state of Wyoming has about 27,155 miles of unpaved roads throughout its various counties (Patritch, 1993). The management of these unpaved roads fall under the jurisdiction of various state and federal agencies. For instance, the Forest Service is responsible for 6000 miles of unpaved roads in the Medicine Bow District alone. These unpaved roads range from those that are no longer in use to high-volume two-lane unpaved roads.

If traffic on an unpaved road reaches a volume high enough to justify the cost, it will usually be paved. Until that time, the unpaved roads must be maintained to protect the original investment, to protect the surrounding environment, and to insure user safety. Roads that are taken out of service still require maintenance to prevent erosion. Other roads in the system require maintenance ranging from filling holes to reducing dust levels.

Maintenance may include the repair of isolated damage areas, reconstruction, or scheduled preventive maintenance. Isolated damage areas include ruts, potholes, and corrugations (washboarding). Reconstruction includes construction and repair of ditches, the addition of soil stabilization materials to the road surface, etc. The use of a dust palliative is one form of preventive maintenance. Dust palliative use results in better visibility and thus increases safety and user comfort. It also reduces the loss of fines from the road surface. The right palliative, correctly applied, may also increase soil strength, thereby reducing the amount of blading required to repair damage.

The objective of this manual is to provide maintenance guidelines for personnel who have road maintenance responsibilities.

Road Classification and Maintenance Requirements

Roads are classified in a variety of ways by federal, state, and local agencies. Roads may be classified according to status, usage, user comfort, surface material, volume of traffic, or function. The status of a road refers to its accessibility to traffic. A road may be classified as "open," "closed," or "closed seasonally." Usage relates to the types of vehicles that use the road, e.g., four wheel drive, high clearance, or general. Road user comfort is based upon the comfort level experienced by vehicle operators who use the road. User comfort is affected by such things as smoothness of ride a user may experience, and driving skill needed to travel safely on the road. On unpaved roads, surface materials that are used include native soils, gravel, or a combination of these materials. On paved roads, surface materials include concrete and bituminous products such as asphalt. Volume of traffic is a measure of traffic that depends upon the type and the number of vehicles that travel over a road in a specified time. Often the volume of traffic is measured in terms of equivalent axle load units (e. g., units of 18 Kips). For example, the volume of traffic may be stated in terms of the number of equivalent 18 Kips axle load units that travel over the road per day. A passenger car may be equivalent to only a fraction of a unit axle load; whereas, a logging truck may be equivalent to several unit axle loads. Roads may also be classified as to their function. For example, they may be classified as arterial, collector, and local roads. In rural Wyoming, most local roads are unpaved.

Road Classification

A publication by the Wyoming State Highway Department Planning Branch (1981), classifies highways by function. Rural roads are classified as: Rural Arterial, Rural Collector, and Rural Local. Rural Local roads consist "of land service roads designed for low speeds and low traffic volumes" (Planning, 1981). While this publication does not classify Rural Local roads as paved or unpaved, a study of the map enclosed in the publication shows that the majority of rural local roads are unpaved.

The Wyoming Highway Department classifies unpaved roads into categories B, C, E1, and E2. Roads classified as B are bladed native soil. Roads classified as C are bladed and drained, but gravel is not added to the road surface. Class E1 roads are bladed, drained and gravel aggregate has been added where needed. Class E2 roads are aggregate surfaced, bladed and drained (Patritch 1993).

The U.S. Forest Service classifies roads in their system by maintenance levels. Some of the factors considered in the selection of maintenance levels are:

1. Resource program needs, environmental and resource protection requirements, visual quality objectives, and recreation opportunity spectrum classed,
2. Road investment protection requirements,
3. Service life and current operational status,
4. User safety,
5. Volume, type, class, and composition of traffic,
6. Surface type,
7. Travel speed,
8. User comfort and convenience,
9. Functional classification,
10. Traffic service level (USDA Forest Service, 1992).

These factors are used by the USDA Forest Service to determine into which of the following maintenance levels a road will be placed.

LEVEL 1. Assigned to intermittent service roads during the time they are closed to vehicular traffic. The closure period must exceed 1 year. Basic custodial maintenance is performed to keep damage to adjacent resources to an acceptable level and to perpetuate the road to facilitate future management activities. Emphasis is normally given to maintaining drainage facilities and runoff patterns.

LEVEL 2. Assigned to roads open for use by high clearance vehicles. Passenger car traffic is not a consideration. Traffic is normally minor, usually consisting of one or a combination of administrative, permitted, dispersed recreation, or other specialized uses. Log hauling may occur at this level.

LEVEL 3. Assigned to roads open and maintained for travel by a prudent driver in a standard passenger car. User comfort and convenience are not considered priorities; typically low speed, single lane with turnouts and spot surfacing. Some roads may be fully surfaced with either native or processed material.

LEVEL 4. Assigned to roads that provide a moderate degree of user comfort and convenience at moderate travel speeds. Most of these roads are double lane and aggregate surfaced. However, some roads may be single lane. Some roads may be paved and/or dust abated.

LEVEL 5. Assigned to roads that provide a high degree of user comfort and convenience. These roads are normally double lane and paved. Some may be aggregate surfaced and dust abated (USDA Forest Service 1992).

The Forest Service classification of unpaved roads is extensive. However, other classifications are useful. For example, the Wyoming Department of Transportation (WDOT) classification of unpaved roads may be related to the Forest Service (USDA-FS) classification as shown in the following listing:

USDA-FS	WDOT
Level 1	Closed
Level 2	B

Level 3	C
Level 4	E1
Level 5	E2

Often the traffic volume on these roads varies widely with the season. Therefore, some of these roads may be closed seasonally.

Maintenance Requirements by Road Type

Level 1: Closed roads. Roads that have been closed to traffic must be maintained to prevent erosion even if their closure is temporary. Soil erosion has been a serious problem throughout the United States. Hence, the prevention of erosion is a high priority item. In the Rocky Mountain region erosion is a natural occurrence, because of the steep terrain, and the effects of rain and snowfall. However, man-made erosion, due to road building and use, can cause severe damage to the environment.

Maintenance of Level 1 roads is usually limited to the placement of water bars and to vegetation seeding. If this is properly done when the road is first closed, minor additional maintenance can insure that erosion is reduced. If roads have been well maintained before closing, only preventive maintenance such as seeding may be required once the road is closed. Quick action will reduce soil loss to erosion, and seeding activity should be scheduled as soon as possible after closure, if the road is to remain closed long enough for seeding to be practical. After preliminary maintenance on a closed road has been completed, additional maintenance needs should be evaluated periodically, and performed as appropriate.

Some roads that have been closed to regular vehicle traffic may remain open to special users. These special user activities may require continued maintenance. For roads restricted to foot and bicycle traffic, little maintenance will be needed once native grasses have been re-established. Roads that are open to vehicles of less than forty inches in width may require additional maintenance of water bars. A yearly maintenance inspection of the roads is suggested.

Level 2: Four Wheel Drive—High Clearance Roads. Once established, these roads are seldom bladed. However, drainage structures may be needed to prevent erosion, and to reduce damage such as large ruts and pot holes. If pot holes and ruts are not filled, drivers will tend to go around them, spreading out the area of damage. As a result, the roadway may become much wider than the original track. Culverts, ditches and water bars are the most commonly used drainage structures.

The maintenance of Level 2 roads can be expensive. To keep costs down, in some forest areas the Forest Service has sought the assistance of volunteer groups that have a special interest in maintaining the road. Work squads, supplemented with volunteer workers, can stabilize soft wet areas, and can fill pot holes and ruts in a relatively short time. While volunteers cannot always be recruited, volunteer road work can result in great savings for the Forest Service, state and counties.

Level 3: Low Volume Unpaved Roads. These roads deteriorate from usage and the effects of weather. While the volume of traffic on these roads may not justify the use of a dust palliative or soil strengthener, these roads do require periodic maintenance. The most common form of maintenance on these roads is blading. The repair of potholes, ruts, and corrugations requires blading. To minimize damage to roads during wet weather, drainage facilities must be maintained. A periodic inspection of these roads should be made, and maintenance scheduled to correct any deficiency found.

Level 4: High Volume Unpaved Roads. Unpaved Level 4 roads require the maintenance of Level 3 roads, plus maintenance that is particular to Level 4 roads. The road surface must be bladed to repair damage and to re-establish the crown at an angle sufficient to allow water to drain from the road surface. Occasionally, aggregate must be added to meet traffic needs without the necessity of continual blading.

Preventive maintenance on Level 4 roads may also be required to slow deterioration of the road. This preventive maintenance may take the form of establishing proper drainage, blading to re-establish the crown, or to move coarse material from the road shoulder back to the road bed. One additional form of maintenance is the use of soil stabilizers.

Level 5: High Volume Roads—High Degree of User Comfort. Unpaved Level 5 roads require frequent blading and maintenance of drainage structures. In addition, soil stabilizers and dust palliatives may be required to improve safety, air quality, and ride quality. In areas where high volume of traffic requires nearly constant maintenance, the addition of soil-stabilization additives may reduce the required maintenance. Additional information on additives may be found in Appendix A.

Maintenance Activities and Scheduling

As noted above, maintenance requirements vary with road type. Maintenance procedures may also vary with road type. The type of water bar used on a closed road may differ from that required on a road designated for use by four wheel drive vehicles. The type of damage experienced by Level 2 roads may differ from that experienced by Level 5 gravel roads.

So, too, the scheduling of maintenance will vary. Level 1 roads may need maintenance only a few times after their closure. Because of excessive cost per user, repair of Level 2 roads may be limited to only the most severely damaged areas. Level 3 roads may be scheduled for maintenance once every few years or so, with emergency repairs being performed as needed. Level 5 roads may require frequent or continual maintenance. The following discussion pertains to maintenance activities and suggests how maintenance can be scheduled.

Drainage: One of the most important maintenance activities is the improvement of drainage. Proper drainage results in a reduction of the weakening effect that water has on the soil, and therefore, a reduction of damage to the road surface. The following equation relates the shear strength of soil to cohesion and water content (McCarthy, 1988).

$$\Gamma = c + \sigma \tan \varnothing \qquad \text{(E1)}$$
$$\sigma = (\gamma - u_w)d$$

where:
Γ is the shear strength of the soil in psf
c is the cohesion of the soil in psf
γ is the weight of the soil in pcf
d is the depth, in feet, at which the shear strength is being calculated
u_w is the weight of water in pcf, and
$\varnothing$ is the friction angle of the soil in degrees

If the soil is drained, u_w is decreased and the shear strength of the soil is increased. For instance, consider the case where the soil is saturated (say the road surface is at the water level). Let c = 100 psf, d = 1 ft., σ = 118 pcf and $\varnothing$ = 30°. Then, one foot below the surface, the soil has a shear strength of 132 pounds per square foot. The same soil has a shear strength of 168 pounds per square foot when it is not saturated (drained with u_w = 0, i.e.,the road surface well above water level). This equation also shows that increasing the cohesion of the soil will increase the shear strength of the soil. The cohesion of a road surface material might be increased by adding soil that has high cohesion or by applying chemical additives.

In addition to increasing the strength of a soil, good drainage also reduces the loss of fines. The fines in a soil are a source of cohesion. As demonstrated above when the cohesion of a soil increases so does its strength. When water stands on a gravel road, the action of tires rolling along ruts and over puddles mixes the soil with the water. The fines stay mixed with the water longer than the coarser material. With additional vehicle traffic, the fines are splashed out with the water as the tires pass along ruts and over puddles. This action increases the depth of the puddles, which causes pot holes to form, and fines to be lost from the roadbed.

Ditches: The addition and/or maintenance of a properly designed drainage ditch will improve the drainage of the roadway. The required cross sectional area and slope of a ditch may be determined from runoff charts and ditch capacity tables or by determining the required flow rate and using the Manning equation (Irwin & Nieber, 1975).

In level or near level areas, ditches must be maintained to carry the water away from the road. If the ditch is not carrying water away, the slope of the ditch should be checked. The slope should be at least 0.5%, that is the ditch should drop 1/2 foot for every 100 feet of length (Hudson et al., 1987). Because water will flow more easily over a smooth surface, ditches must be kept free of debris. Vegetation in the form of grasses prevents erosion, but trees and other obstacles in a ditch will prevent water from flowing freely.

If the slope of a ditch is steep, water may flow too freely. In this case, placement of obstacles in the ditch to slow the flow may be necessary. One of the easiest methods of slowing water flow in mountain areas is to place rocks in the ditch. In other areas, short concrete piles or bales of straw are placed in the ditch to absorb some of the water's energy as it flows down the ditch. If rocks are used, they must be large enough so that the water will not wash the rocks down the ditch. If bales of straw are used, they must be pegged down to keep the water from washing them down the ditch.

Culverts: Culverts or diversionary dams may be necessary to drain or to divert water away from the roadway. Culverts must be keep free of debris and sediment to function properly. Logs and brush may be carried down ditches and lodge in the entrance of a culvert. If this happens, the debris must be removed.

Occasionally sediment will form in a culvert. This usually happens when the exit to the culvert is blocked or, when drainage away from the exit is insufficient. The blockage must be eliminated, or the drainage problem remedied, and the sediment removed before the culvert can function properly. Once the blockage or drainage problem is solved, sediment may be removed from the culvert by using a pole with a hoe-like device attached, or by using water under pressure to hydraulically remove the sediment.

Proper drainage is also necessary to remove water from the road surface. When water flows down tire tracks of a road it causes erosion. In time, this erosion causes ruts, and over more time these ruts become gullies. Water bars and crowning are two common methods of removing water from the road surface.

Water Bars—Their Placement and Design: Water bars are usually used where a crown cannot be maintained. Water bars are placed along the roadway to reduce the amount of water flowing down the road. Because road usage may tend to destroy water bars, the water bars may be made of some material other then native soils. Four types of water bars are shown in Figures 1-4.

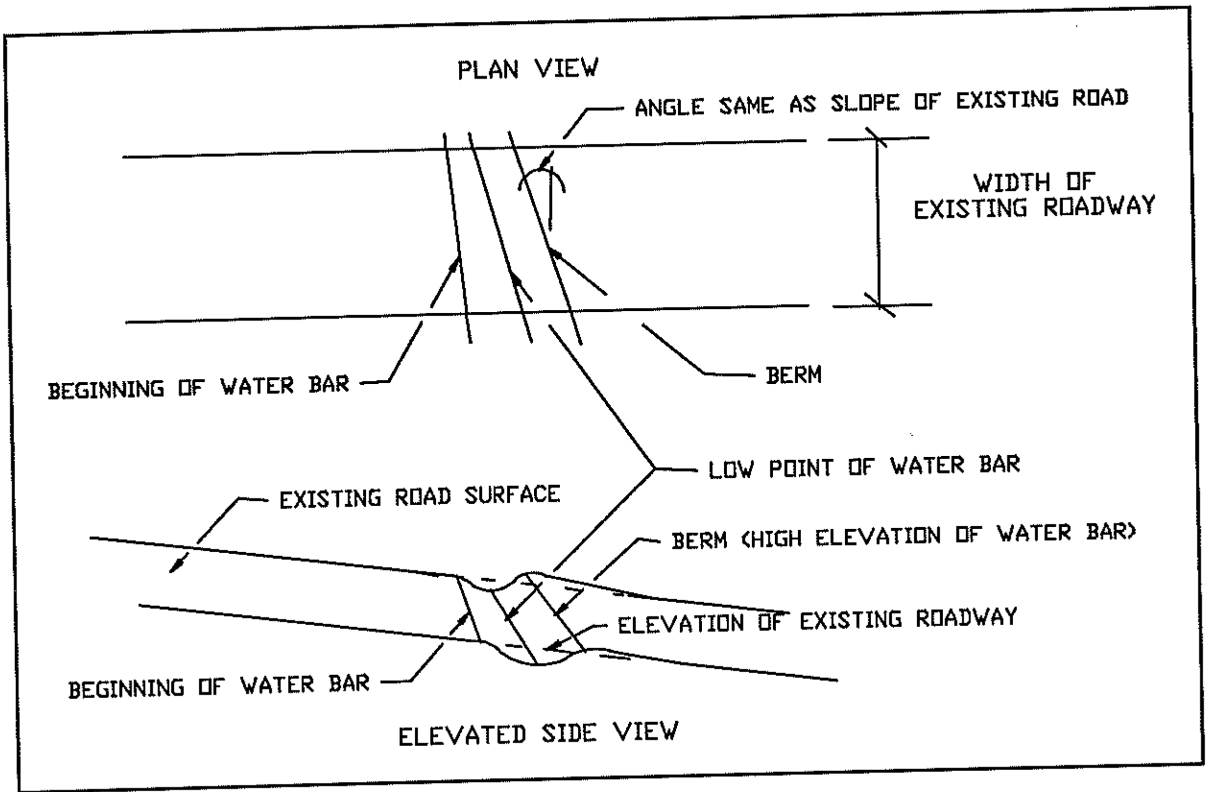

FIGURE 1. Soil Water Bar

Figure 1 shows a soil water bar. Soil water bars are shallow ditches that run diagonally across the road. Soil from the ditch is placed in a berm on the down hill side of the ditch. Native soils are used for the construction of these water bars. They can be constructed with a motor grader, bulldozer, or by hand (e.g., using a pulaski). Soil water bars are appropriate for areas that are to be seeded with native grasses or other form of vegetation and that experience only foot or light bicycle traffic. Because of motorized, horse, or heavy bicycle traffic, the berm of a soil water bar may be damaged so that it no longer serves its purpose.

Figure 2 shows a sketch of a rock water bar. The rocks are to reinforce the berm of the water bar. Rock water bars may be constructed by using a backhoe to dig a trench. Rocks that are placed in the trench should be fairly large. However, they should protrude only a few inches above the original road surface. The soil from the ditch on the uphill side

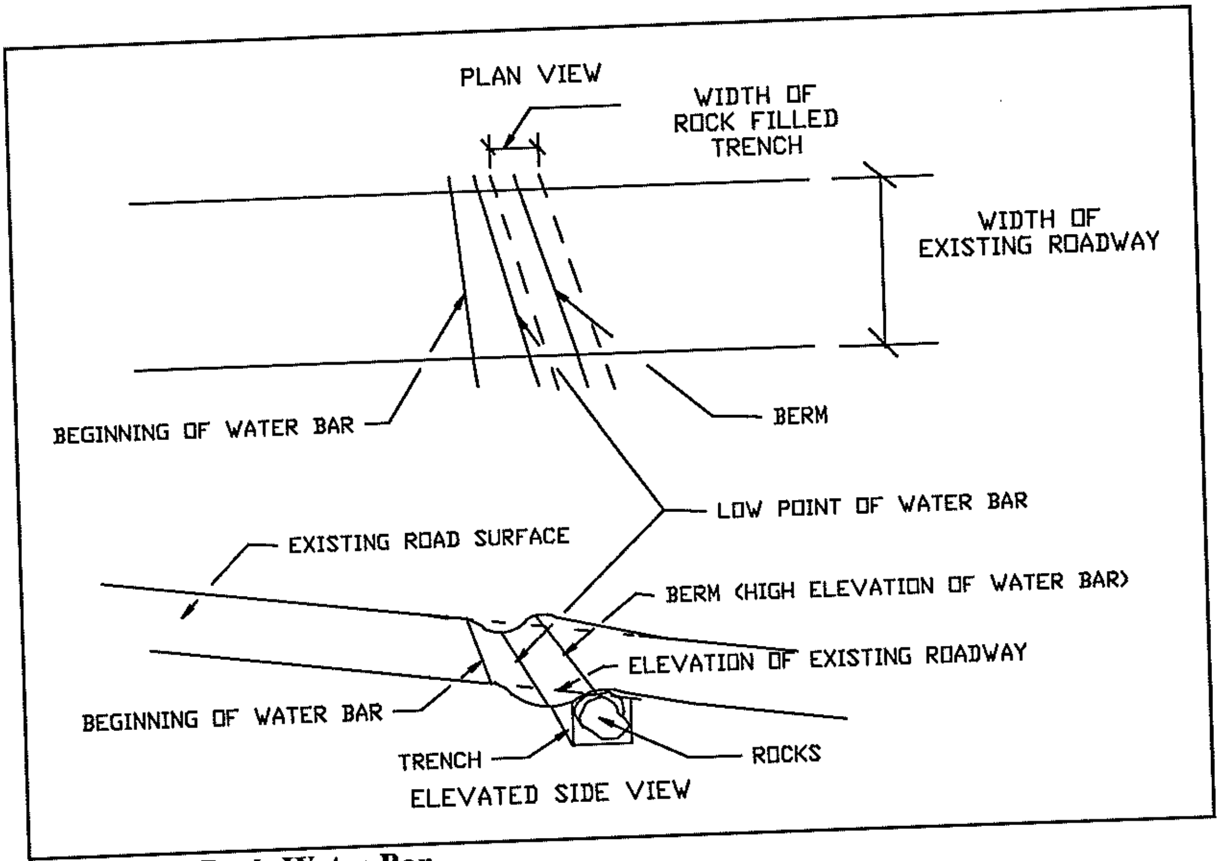

FIGURE 2. Rock Water Bar

of the water bar should be used to cover the rocks, and to slope the berm back to the elevation of the road surface on the downhill side. Rock water bars may be used with any type of traffic.

Figure 3 shows a sketch of a log water bar. As with rock water bars, the log is to reinforce the berm and a backhoe is handy for construction. The log placed in the trench should be large, should protrude a few inches above the previous road surface, and should be pinned down or wedged with rocks at the ends. Log water bars are sometimes easier to construct than rock water bars, but are less durable.

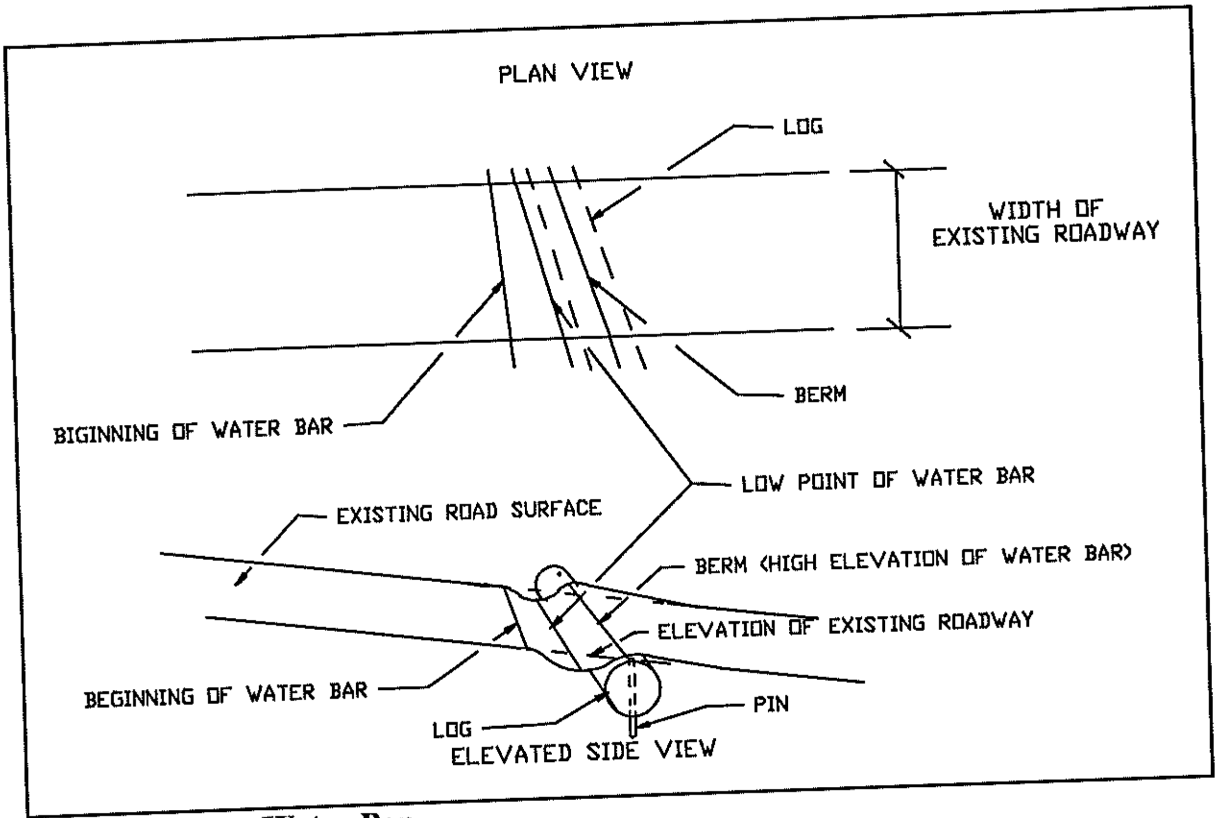

FIGURE 3. Log Water Bar

Figure 4 is a sketch of a rubber water bar. The timbers making up the two sides may be of any size, as may the strip of rubber. Used conveyer belts make good strips for the center of the water bar. The timbers used to construct a rubber water bar should be treated to slow decomposition caused by contact with the ground. Rubber water bars serve the purpose of removing water from the roadway, are durable, and are reasonably easy to construct. Because the rubber strip gives when a vehicle crosses it, the vehicle experiences only a small bump. For this reason, rubber water bars are recommended on roads where the speed bump effect of soil, rock, or log water bars is not safe, or desirable.

The slope of a water bar as it crosses the road should be approximately the same as the slope of the road. The depth of the water bar only needs to be a few inches. The exit of the water bar should be such that water from it drains easily onto the surrounding area or into a ditch. Gravel or rocks should be placed at the exit in such a manner that they do not

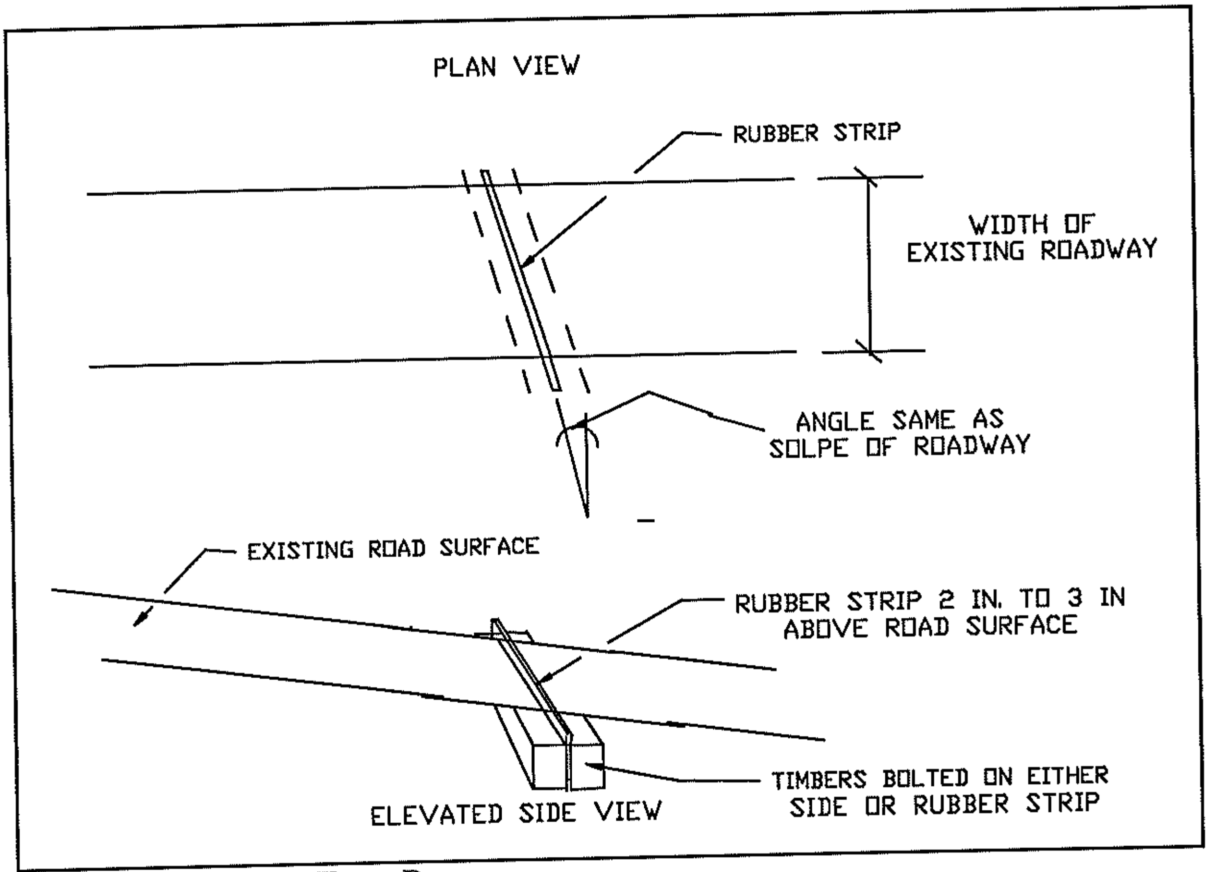

FIGURE 4. Rubber Water Bar

block the exit but will help to prevent erosion. Water bars should be used on hills, wherever there are signs of erosion and where drainage away from the road is possible. The water bar should be placed above the eroded area, to prevent water from flowing through the eroded area and increasing the damage.

Properly designed and constructed water bars tend to be self cleaning. However rocks and chunks of wood sometimes enter the exits and drainage ditches. As a result, the water bar may fill with sediment. Obstructions to drainage and accumulated sediment must be removed for the water bar to function properly.

Vegetation: Vegetation is used to reduce the amount of soil lost to erosion. A five-year study of several U.S. roadside slopes of bare ground and slopes with full vegetation cover, has shown that the loss of soil on bare slopes was between 78 and 234 ton/acre/yr, while the loss of soil for a slope covered by vegetation was 4.9 ton/acre/yr (Richardson et al, 1970). If an eight-foot-wide road way is reduced to a two-foot-wide foot or bike path, and native grasses are planted, the area of soil covered by vegetation is increased by nearly 3/4 of an acre per mile.

If a road has been closed to all but vehicles forty inches and less in width, the effect of planting grasses may not be as dramatic. However, if the width of bare soil in an old roadway is reduced from eight to five feet in width, the area of soil covered by vegetation is increased by 1/3 of an acre per mile. These numbers show the importance of seeding roads as soon as possible after they are closed.

Vegetation is also used to prevent erosion on road sides and in ditches. Different areas may require different types of seed and different methods of planting. For example, in some areas mulching may be required to protect the seeded area. One form of seeding that has met with success is to spray pre-germinated, wet grass seed onto presoaked embankments. The embankments are then mulched with straw to prevent erosion while the seeds take root (Ross, 1988).

Repair of Deep Ruts and Potholes on Level 2 Roads: Because Level 2 roads are usually native soils, the repair of pot holes and ruts is not always done by blading. Pot holes and deep ruts on Level 2 roads can be filled by placing large rock in the bottom and then smaller rocks on top. Low areas that have a tendency to develop pot holes and ruts should be drained, or if possible, roads rerouted to higher ground.

In boggy areas, where draining or moving the road is not practical, geotextile cloth may be placed on the fine saturated soil. The cloth should then be covered by a thick layer of unsaturated coarse soil. For a geotextile cloth with a modulus of 224 Kips, and a cover soil with a cohesion of at least 300 PCF, one foot of material over the cloth is required

(Giroud, 1981). This amount of material over the cloth also allows the road surface to be bladed without damaging the geotextile cloth. In addition, the cloth keeps the two grades of soils separated, so that the unsaturated coarse soil does not sink into the fine saturated soil. The cloth also tends to prevent moisture from migrating into the unsaturated coarse soil.

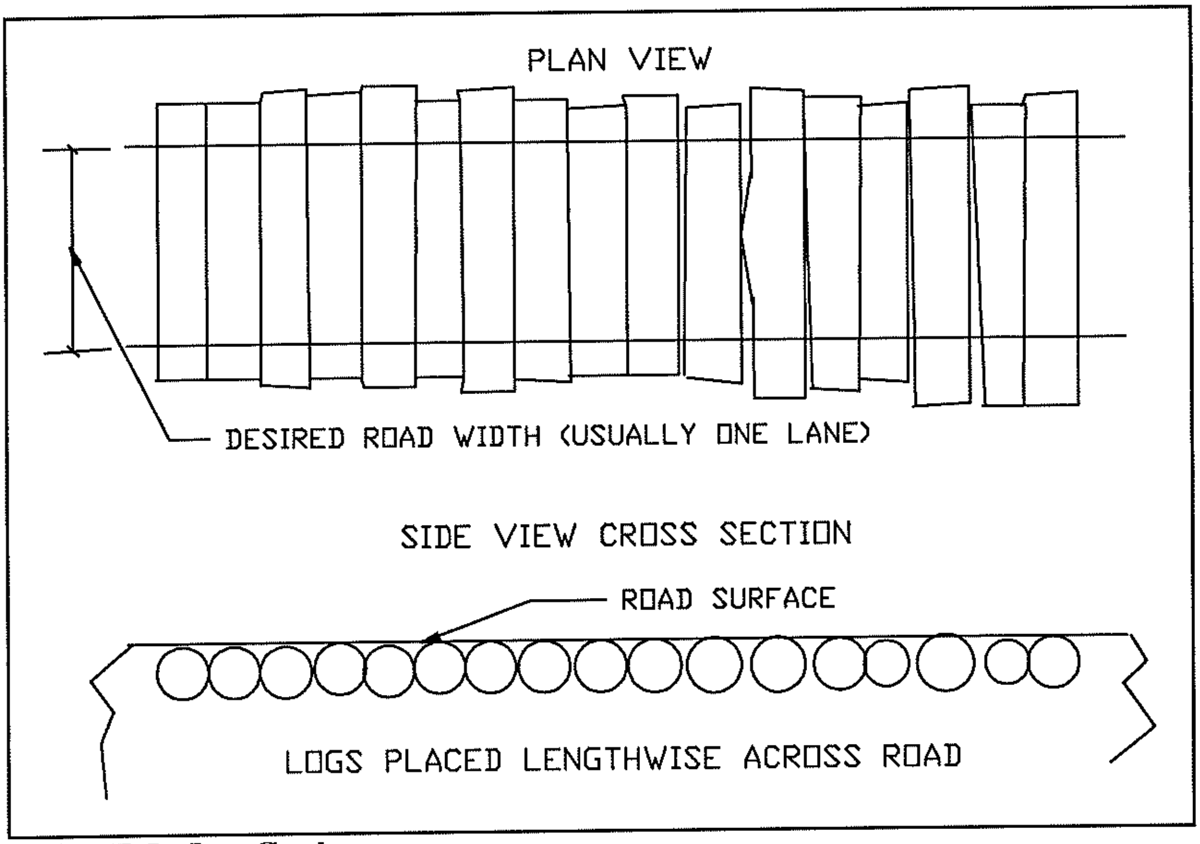

FIGURE 5. Log Corduroy

Another method of reinforcing a boggy area is to corduroy the road with logs (see Figure 5). This technique is labor intensive, but it is effective, and may be the best alternative where hauling fill or aggregate is difficult or cost prohibitive.

A road may also be reinforced with landing craft matt. Landing craft mats are long, flat, steel runners with holes all along the surface (see Figure 6).

Blading: Blading or grading is the most common form of maintenance for unpaved roads. Good blading practice results in a smooth road surface. It moves the surfacing

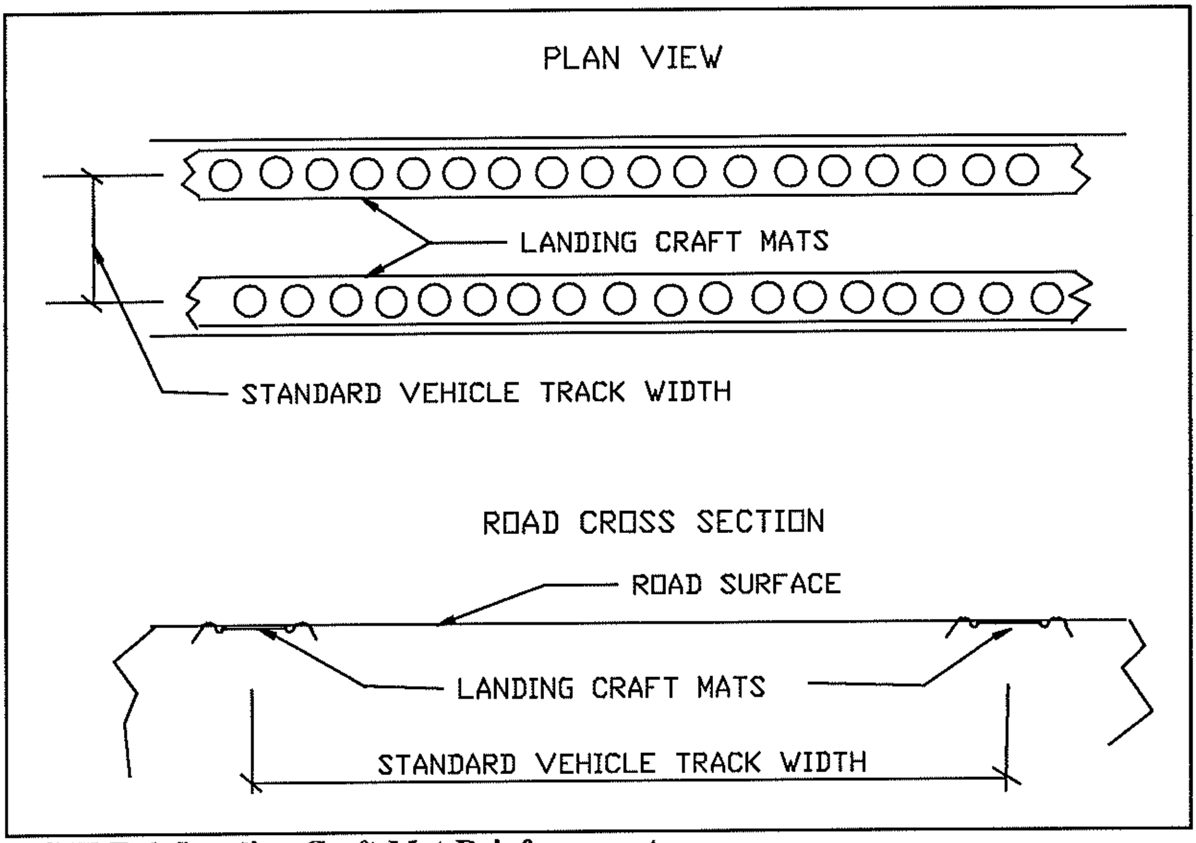

FIGURE 6. Landing Craft Mat Reinforcement

material back toward the center of the road, and re-establishes the proper crown (National Associatin of County Engineers, 1974. Ross, 1988. Hudson et al, 1987). As a result, the water is able to flow off the roadway, and the damaging effect of water on the road is reduced. Blading also eliminates ruts, potholes, and corrugations. Thus, damage to vehicles and safety hazards are reduced. "The frequency of blading will depend on the characteristics of the surface material, the environment, traffic level, and the acceptable level of smoothness" (Transportation Research Board. 1979a). Moisture is necessary for productive blading. For this reason blading activities are best scheduled in cold climates as soon as possible after the frost has left the roadway. When blading is needed during dry periods, it may be necessary to water the road surface before and during blading (Srombom 1987). Some preventive maintenance activities accomplished by blading are:

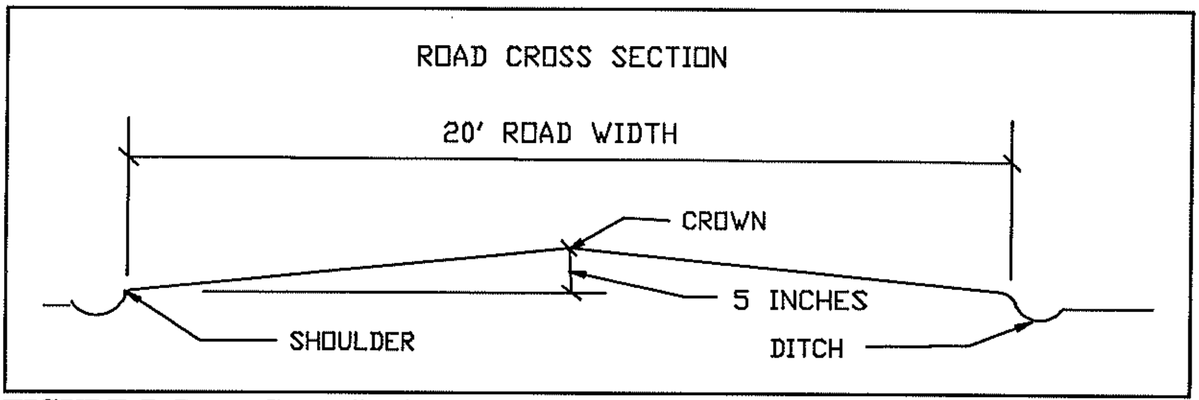

FIGURE 7. Road Cross Section, Crown Slope

Crowning: Crowning is a process that makes the center line of a road higher than the edges (see Figure 7). By crowning the surface of the road the amount of water on the road can be reduced, resulting in a reduction in the loss of fines. The slope of the road should increase by 1/2 inch per foot of width from shoulder to center line. For a road 20 feet wide this means the center line should be 5 inches higher then the shoulder (Transportation Research Board 1979b, Ross 1988).

Where a cattle-guard crosses the road, the crown of the road must be sloped to meet the edges of the cattle-guard smoothly. If a secondary road intersects a through road, the through road should maintain its crown, and the slope of the secondary road should smoothly meet the surface of the through road.

Shoulder Restoration: Usually the process of moving course material from the shoulder of the road toward the center line is accomplished at the same time the crown is being re-established. There are two reasons for moving the soil from the shoulder toward the center. One is to keep the road surface material on the road. The other is to remove the berm that is formed at the edge of the road. This berm restricts the flow of water into the ditch, causing puddles to stand at the road edge (see Figure 8).

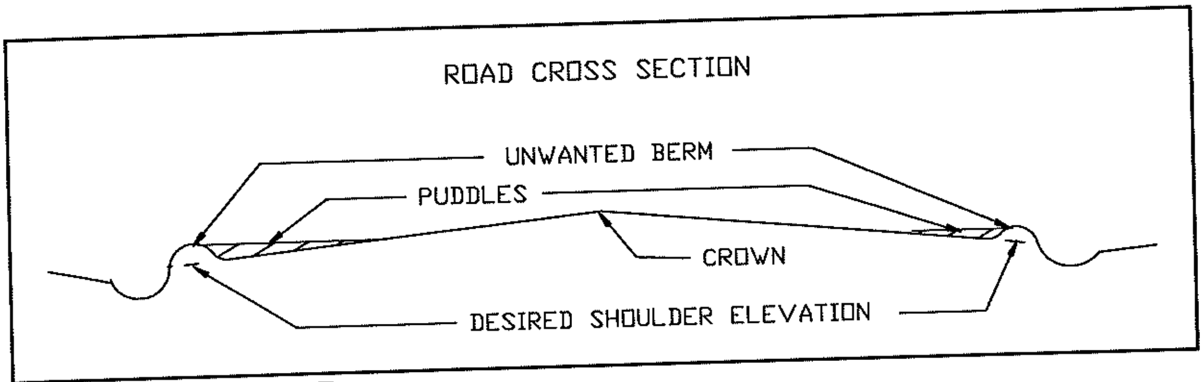

FIGURE 8. Shoulder Berm

To re-establish the proper profile of the crown and shoulder, the blade of a grader is used to cut along the shoulder of the road, at a slope equal to or slightly greater than the desired crown slope. The material is then moved into a windrow near the center of the road. After this has been done for both shoulders, the material in the windrows is graded so that the crown is re-established (National Association of County Engineers, 1974).

Damage Repair: One of the methods used to restore a road surface is for a grader operator to blade damaged areas and then resurface. Care must be taken to cut below the bottom of ruts, potholes, or corrugations in the damaged area. If the operator makes a cut only deep enough to remove gravel from the high points to fill the low points, the bladed road will have soft and hard areas. The tops of the high points that were cut will have been hardened by traffic, while the low points will have been filled with loose gravel. After a short period of use, the soft filled areas will be packed and lowered relative to the hardened high areas, and the ruts, potholes, and washboards will be redeveloped by traffic.

Instead of using the blade, the damage area should be loosened with a scarifier, then the blade should be used to smooth the entire road surface in that area and re-establish the crown. If possible, water should be added to the loose soil, and after the road surface is smoothly bladed it should be compacted (Martinez, 1993). This method of repair will extend the life of the repaired area.

Another method of correcting localized problems on unpaved roads is to place and compact new aggregate in the damaged areas. This activity is called patching. After the aggregate used in patching is placed on the area to be repaired, water should be added. After the water is added the area should be smoothed and compacted.

If an area on a road must be patched or bladed often, the source of the problem should be evaluated. If the problem is caused by poor drainage measures, as discussed earlier, steps should be taken to improve drainage. If the problem is caused by inferior material, the inferior material should be removed and replaced with higher quality aggregate (Hudson et al. 1987).

Dust Abatement: In some areas, dust abatement is required by the Environmental Protection Agency (EPA) to improve air quality. In other areas dust abatement may be necessary to improve safety, or to improve the quality of user comfort, either for the road user or for people who are using areas near the road. Secondary benefits of the use of dust abatement additives may be a reduction in loss of fines, or an increase in the strength of the road surface (see Manual Appendix A).

Dust abatement may be accomplished by watering, but this process is expensive over the long term. The use of chemicals that draw moisture from the air is a better approach to long term dust abatement. These chemicals are mixed with the road soils and may continue to control dust for up to a year. The chemicals used in dust control may be spread over the surface of the road using a sprinkler truck, or they may be worked into the soil using the following method:

> First the top two or three inches of the road surface is moved into windrows on either side of the road. Then, half of the recommended application is applied to the exposed surface. Next, the soil from the sides

of the road is moved back toward the center, and the last half of the chemical is applied to the road surface. The blade of a grader can now be used to mix the chemicals and the soil. Finally, the surface of the road should be compacted using roller or tire compaction (G. Moats 1993). If this method is used to apply a dust palliative, usually the effectiveness of additive is improved.

The following list of dust palliatives and the recommended quantities is taken from *Surface Design and Rehabilitation Guidelines for Low- Volume Roads* (Hudson et al., 1987).

Description of Chemical Additive	Quantity Gal/yd^2
Polyvinyl acetate diluted 1 to 20 of water	0.40 - 0.70
Trade name diluted 1 to 10 of water	0.30 - 0.50
Butiadene styrene rubber and resin in oil emulsion diluted 1 to 20 or water	0.70 - 1.50
Petroleum resin emulsion diluted 1 to 14 of water (only if local water supplies are not affected)	0.70 - 1.30
Thermoplastic resin diluted 1 to 9 of water	0.70 - 1.30
Wax thermoplastic resin diluted 1 to 9 of water	0.70 - 1.30
Vinyl acetate copolymer diluted 1 to 16 of water	0.40 - 0.70
Petroleum resin (only if local water supplies are not affected)	0.25 - 0.40

Acrylonite butiadene styrene copolymer diluted 1 to 20 of water	0.40 - 0.70
Urea formaldehyde resin diluted by 40 percent water	0.25 - 0.40
Combination of lignin sulphonate and sodium methylate diluted 1:4 and 1:40 to water respectively	0.07 - 1.30
Calcium chloride	0.30 - 0.40
Magnesium chloride	0.30 - 0.40
Lignin sulfonate	0.70 - 1.30
Dust oil	0.20 - 0.40

Because this list was compiled in 1987, new laws regarding the use of these chemicals should be checked before any application is made.

Conclusion

The majority of roads in the U.S. and Wyoming are unpaved. Care and maintenance of these roads costs tax payers millions of dollars annually. It is in the best interest of people in charge of maintaining these roads to do so in the most cost efficient way possible. For example, it may be quicker, and in the short term, cheaper to blade the damaged area of a road. However, in the long term, it will be more cost effective to scarify the damaged area, water, blade, and re-compact the soil. The paper by Hudson, et al. (1987) suggests maintenance procedures that will help ensure the investment of the tax payer, protect the environment, and increase user comfort and safety.

Selected References

Eaton, R.A., Gerard, S., and Gate, D.W. *Rating Unsurfaced Roads.* Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Lebanon, NH, 1988.

Giroud, J.P., and Noiray, L. "Geotextile-Reinforced Unpaved Road Design." *Journal of the Geotechnical Division,* ASCE, 10(No GT 9):1233-1254, 1982.

Irwin, Lynne H., and Nieber, John L., (1975). *A New Approach to Highway Drainage Design.* Low-Volume Roads, Special Report 160, pp 92-103. Washington, DC, 1975.

Hudson, S.W., B., McCullough, F., Carmicheal, R.F. *Surface Design and Rehabilitation Guidelines for Low-Volume Roads.* Federal Highway Administration, U.S. Department of Transportation. Washington, DC, 1987.

Martinez, Al. USDA Forest Service Medicine Bow National Forest, Laramie, WY. Interview, Feb. 12, 1993.

McCarthy, D.F. *Essentials of Soil Mechanics and Foundations,* 3rd. Ed., p.224. Englewood Cliffs, NJ: Prentice Hall, 1988.

Moats, Gary. USDA Forest Service Medicine Bow National Forest, Laramie, WY. Conversation, May 10, 1993.

National Association of County Engineers. *Blading Aggregate Surfaces.* National Association of Counties Research Foundation, Training Guide Series, 1974.

Patritch, Mike. Wyoming Department of Transportation, Cheyenne, WY. Telephone interview, May 12, 1993.

Wyoming State Highway Department. *A Digest of the Wyoming State Highway Plan,* pp. 7-8. Wyoming State Highway Dept. Planning Branch, 1981.

Richardson, E. C., Diseker, E. G., and J. M. Sheridan. *Practices for Erosion Control on Roadside Areas in Georgia.* Highway Research Record, NO. 335, HRB., USA, pp. 99-104, 1970.

Ross, S. S., and K.B.Woods, (Eds.). *Highway Design Reference Guide.* New York: McGraw-Hill, 1988.

Srombom, R. *Maintenance of Aggregate and Earth Roads.* Office of Implementation, Research, Development, and Technology, Turner-Fairbank Highway Reserch Center, McLean, VA, 1987.

Transportation Research Board. *Maintenance of Unpaved Roads.* Synthesis 1, p. 26. Washington, DC, 1979a.

Transportation Research Board. *Transportation Technology Support for Developing Countries.* Compendium 7 Road Gravels, Text 8. National Academy of Sciences, Washington. DC, 1979b.

Transportation Research Board. *Transportation Technology Support for Developing Countries.* Compendium 7 Road Gravels, Text 8. National Academy of Sciences, Washington. DC, 1979b.

USDA Forest Service. *Transportation System Maintenance Handbook.*. WO AMENDMENT 7709.58-92-1, pp. 3-5. Washington, DC, 1992.

MANUAL APPENDIX A

Soil Additives

Introduction

The use of additives to strengthen and stabilize road surfacing soils has increased as the cost of road maintenance increases. Because of this increased use of additives, and the increasing cost of their application, it is important to attempt to find a method to predict what additive will best accomplish the desired goals of strengthening the road surface and abating dust.

Stabilization

The stabilization of soil can be divided into the following three methods:

1. Mechanical methods, (such as compaction, drainage, and mixtures) that increase stability without the addition of foreign material,
2. Physical methods (such as temperature change, hydration, evaporation, and adsorption) in which physical reactions lead to stabilization,
3. Chemical methods that cause ion exchange, precipitation, polymerization, or oxidation (Kezdi 1979).

Often when an additive is used to strengthen road surfaces a combination of these methods is used. For instance when Magnesium Chloride is applied to a road surface, the surface is often loosened, next the Magnesium Chloride is applied, and finally the surface is smoothen and compacted. After the application is complete, the Magnesium Chloride absorbs moisture from the air, and may cause some ion exchange. This combination of techniques improves the soil stability more than simply applying the Magnesium Chloride to the road surface.

Compaction

Compaction is usually included in any combination of techniques used to stabilize an unpaved road surface. Compaction is accomplished by a variety of methods using machinery such as a sheep's-foot roller or a pneumatic roller. For each type of soil to be compacted an ideal or optimum water content is established. Compaction should take place with the soil as near the optimum moisture content as possible. The reasoning behind this is that the addition of water reduces the capillary forces, and decreases the friction between soil particles. By reducing these forces the compactive effort is reduced and higher compaction can be achieved with less cost (Hausmann 1990). When a soil additive is used, it is necessary to find the optimum additive/water ratio that aids in achieving the highest density after compaction. Once compaction is complete, the additive's properties help maintain the soil density and shearing strength.

Reaction of Additives

An additive may react differently on different unpaved road surface soils. Because of these differing reactions, the use of a particular additive is often based on trial and error methods. Trial and error methods are not cost effective, and can result in a deterioration of a road surface if the reaction between additive and soil is adverse.

Most tests that have been conducted on unpaved roads have addressed the use of additives as dust palliatives. However, some information about the surface condition of the road, after application, is available from the tests. A review of these tests can give an indication of the strengthening characteristics of certain additives. For instance, the following information on road surface conditions is available from a test of four additives, used as dust palliatives, on a road in the Gifford Pinchot National Forest in the Pacific Northwest Region:

Road Surface Performance (road 30):

* Lignin Sulfonate showed some rutting by the third week after application, and the condition worsened up to Week 6. Small potholes were prevalent throughout the section until it was bladed 10 months after application.
* Magnesium Chloride developed some washboarding by the fifth week and potholes by Week 6. By Week 9 berms and raveling had developed.
* Calcium Chloride stayed in fairly good condition until Week 7 when it began to show minor potholes and washboarding. By Week 9 a few large potholes and some surface raveling had developed.
* BIO CAT held up well until seven weeks after application when it developed berms, scattered potholes and minor washboarding (Apodaca, 1990).

The lignin sulfonate, calcium chloride, magnesium chloride, were applied by loosening the soil to a depth of 3 inches, then reshaping and prewetting the surface and applying the palliative. The BIO CAT section was loosened to a depth of 4 inches, and the BIO CAT was applied without prewetting the surface. At each inspection, the road surfaces, where additives were applied, were in better condition than the control surface where no additive was applied (Apodaca, 1990).

Unfortunately no information is given as to the road surface soil type. If we assume that the soil is of the same type on all of the test sections, then this information gives some indication of the comparative strength characteristics of the additives.

Additives Products

Apodaca (1990), Kezdi (1979), Scholen & Coghlan (1990) and Srombom (1987) gave, as part of their respective books or papers, recommendations on the use of various dust palliatives. The following is a list of additives and the pros and cons of their use as stabilizing agents compiled from these authors' writings.

PRODUCT DESCRIPTION: Magnesium Chloride - a concentrated brine that draws water out of the air. This product sinks into the road and creates a tight, hard, compact surface that resists abrasion. Dust is controlled by keeping the surface of the road damp. (Magnesium chlorides from industrial metal recovery are not recommended for use.)

Pros	Cons
1. Aids in road surface compaction 2. Readily available 3. Road can be re-graded 4. Rainfall does not totally deteriorate product 5. Limited hazard to workers 6. Lowers freezing point 7. Increases road stability	1. May corrode steel 2. Rain may cause sloppy conditions 3. Minimum curing time of 24 hours 4. Has required relative humidity levels (32% @ 77°) 5. No cementing action 6. High concentration can be toxic to ecosystem

PRODUCT DESCRIPTION: Calcium Chloride - attracts and absorbs moisture from the atmosphere and environment. Dust is controlled by keeping the road surface damp.

Pros	Cons
1. Provides some stability 2. Blading may be reduced 3. Saves aggregate 4. Reduces frost heave 5. Effective for approximately one year 6. Most effective when used on fine granular type soil	1. Had required relative humidity levels (29% @ 77°) 2. Tends to migrate downward through soil. 3. Slightly corrosive to steel 4. May cause sloppy wet conditions 5. High concentrations of leachate may be toxic to ecosystem 6. Gets hot when mixed with water (may burn skin) 7. No cementing action

PRODUCT DESCRIPTION: Lignin Sulfonate - a waste product of the wood pulping process, that is processed to form ammonium lignin sulfonate containing approximately 50 percent solids, usually as concentrated water solutions. Dust is controlled is by gluing and bonding soil particles together.

Pros	Cons
1. Remains slightly plastic, can be re-graded 2. May increase load bearing strength 3. Environmentally safe 4. May mix with calcium carbonate slurry to counteract corrosive effects and increase dust laying capability 5. No relative humidity requirements 6. Limited hazard to workers 7. Weak cementing action 8. Lowers freezing point 9. Adding 0.5% lime extends the effectiveness and provides a tighter road surface with less aggregate loss 10. Recommended particularly for 3/4" minus materials with 20 to 50 percent silts of clays.	1. Sulfuric acid based product 2. Brown/red colored product on vehicles and in runoff 3. Requires lengthy curing time 4. Water soluble and heavy leaching under wet conditions 5. May increase biochemical oxygen demand in water 5. Surface develops rough crust. 7. Surface crust failures quickly spread. 8. Wearing surface needs 4-8% fines 9. May cause corrosion of aluminum 10. Becomes slippery when wet and brittle when dry

PRODUCT DESCRIPTION: Bioenzymes - provide a bacterial culture in an enzyme solution. Exposure to CO_2 causes bacteria to multiply rapidly and produce large organic molecules which attach to the clay molecules in the aggregate. This action blankets the ion exchange points in the clay preventing absorption of moisture. During hydration, after compaction, linkages between closely packed particles improved cementing bonds.

Pros	Cons
1. Clay lumps lose plasticity 2. Uninterrupted light traffic use 3. Non-corrosive 4. Long term stabilization	1. Ineffective in non-clay soils 2. Five days cure time required 3. High initial cost

PRODUCT DESCRIPTION: Petroleum based emulsions (Resins combined with wetting solutions) - dust is controlled by the product cohering to and coating dust particles, to form cohesive membranes that adhere to other particles.

Pros	Cons
1. Long term effectiveness 2. Not water soluble when dry (no leaching after cured) 3. Provides soil stability 4. Suitable for a wide range of soils 5. No relative humidity requirements 6. Does not attract animals 7. Limited hazard to workers 8. Strong cementing action	1. Requires special equipment for application 2. Potholes may develop 3. Does not lower freezing point 4. Long term application may cause road surface to become too hard for blading maintenance

PRODUCT DESCRIPTION: Fly ash - when mixed with low grade aggregates and shales produces increased durability. Usually blade mixed with road surfacing soil at 3 to 15 percent fly ash, watered to optimum and compacted. The optimum fly ash content must be determined by tests such as ASTM D-593 and ASTM D-689. Two types of fly ash are used, Class F which is usually mixed with lime or portland cement, and Class C which is self-cementing. Class C fly ash is most common in the west (Hudson et al 1987).

Pros	Cons
1. Reduction in surface blading 2. Increase in stability 3. Stable in wet weather 4. Effective over long term	1. High PI sections may become slippery when wet (the addition of lime may be used to reduce the PI) 2. Requires curing periods of from 5 to 10 days 3. Fly ash may contain ecologically undesirable materials

There are other agents that can be used to stabilize unpaved road surfaces. Some of these agents (such as Lime Kiln Dust) may harden the surface to such an extent that they cannot be cut with blade or scarifiers (Scholen & Coghlan 1990). Others may be cost prohibitive at this time, (such as Phosphate Mining Waste due to the cost of removing impurities) but improved technology may allow their application in the future (Figueroa 1987).

The preceding list does not include all of the dust palliatives, and stabilizing agents available; however, many commercial agents are basically composed of one or more of these agents (see trade names listed by Apodaca 1990, Scholen & Coghlan 1990). Some of these products have had other chemicals added to improve their performance.

Conclusion

A project is currently underway at the University of Wyoming to study soils, soil stabilizing additives and soil-additive combinations, with the objective of developing models and recommendations for optimal stabilization of Rocky Mountain region unpaved roads. Models for determining the best agent to use on a particular soil type, will reduce the guess work involved in selecting an additive. Hopefully these models and recommendations will be available in the near future for use by personnel involved in choosing dust palliatives.

Personnel involved in the selection of dust palliatives should document and appraise the results of the use of the various palliative and soil combinations. The documentation and analyses of these results should help personnel make knowledgeable decisions on palliative selection for a particular soil type. The effectiveness of the use of proper additives also depends on proper application methods, such as correct water/additive content and compaction. A combination of these techniques should result in savings of road maintenance costs.

Selected References

Apodaca, M., & Huffmon, D. *Dust Abatement Review and Recommendations*, pp. 21-40. Gifford Pinchot National Forest, WA, 1990.

Figueroa, J.L., Zhou, L., and Chang, W.F., (1987). *Use of Phosphate Mining Waste in Secondary Road Construction*, p 59. Transportation Research Board, Washington, DC, 1987.

Hausmann, M.R. *Engineering Principles of Ground Modification*, p.51. McGraw-Hill, New York, 1990.

Hudson, S.W., McCullough, F. and Carmichael, R.F. *Surface Design and Rehabilitation Guidelines for Low-Volume Roads - Final Report*, p. 51. Federal Highway Administration, Washington, DC, 1987.

Kezdi, A. *Stabilized Earth Roads*, p.22. New York: Elsevier Scientific Publishing Company, 1979.

Scholen, D., and Coghlan, S. *Non-Standard Stabilization*. Study No. F-5, Region 4 USDA Forest Service, 1990.

Srombom, R.D. *Maintenance of Aggregate and Earth Roads*. Report No. WA-RD 144.1. Washington State Department of Transportation, Olympia, WA, 1987.